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ANALOG DATA COMPRESSION FOR VERSATILE EXPERIMENTAL KEVLAR ARRAY--ETC(U)
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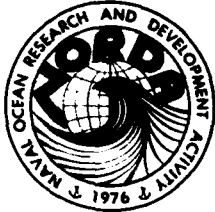


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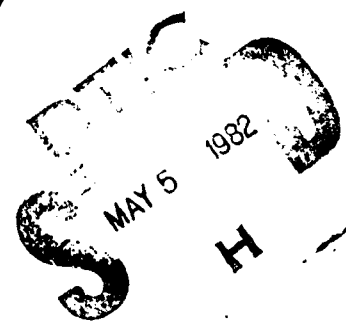
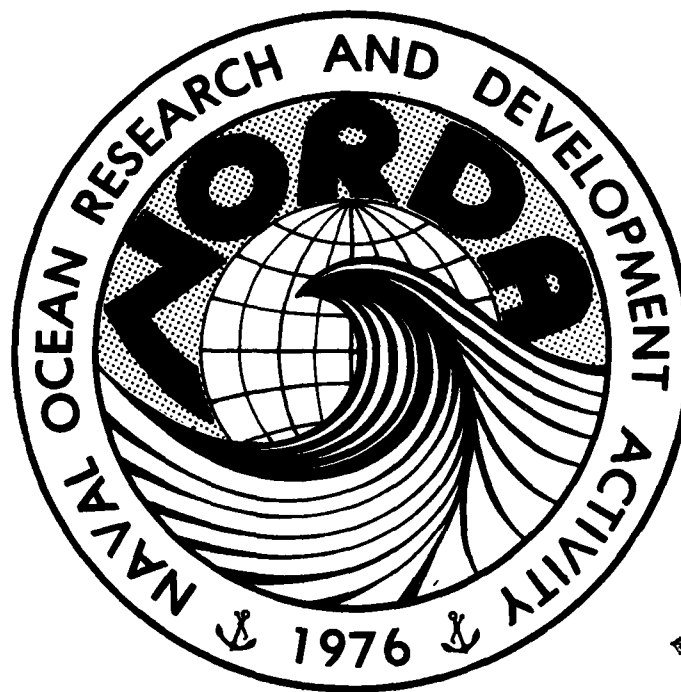
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Analog Data Compression for Versatile Experimental Kevlar Array (VEKA) Telemetry

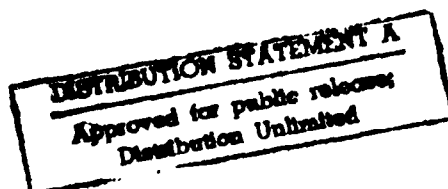


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August 1981



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ABSTRACT

The feasibility of amplitude data compression has been explored with respect to the Versatile Experimental Kevlar Array (VEKA) analog multiplexed telemetry of acoustic data. A Fourier transform approach has been developed to quantify the potential benefits and penalties associated with a particular invertible compression function. Analysis was performed using sinusoidal signals and white noise. Results of the analysis indicate that substantial gains in dynamic range can be achieved with tolerable sacrifices in telemetry system linearity. Specific examples for a particular telemetry system illustrate an increase in dynamic range from 80dB to approximately 120dB.

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Analog Data Compression for Versatile Experimental Kevlar Array (VEKA) Telemetry

I. INTRODUCTION

Multiplexed telemetry, particularly that used to telemeter data from experimental acoustic arrays, frequently suffers from insufficient dynamic range. Dynamic range is defined as the ratio of maximum to minimum allowable signal level for a minimum specified signal to noise ratio. Dynamic range problems are typical in cases where the acoustic experiment involves low level signal measurements (e.g., ambient noise) as well as high level signals from more powerful acoustic sources. Linearity of the telemetry system, however, is typically much better than required for the acoustic experiment. The concept explored here is that of sacrificing an insignificant amount of linearity to achieve an extended dynamic range. This technique of signal processing is known as amplitude data compression and essentially involves amplifying relatively low level signals more than relatively high level signals. Several compression algorithms have been realized in other programs (SEAGUARD, 1979) and analysis has been conducted (Assard, 1981) illustrating the *benefits* of amplitude data compression while much less attention has been devoted to quantifying the simultaneous *detriments*. Closed form analysis is virtually impossible due to the non-linear compression and expansion functions. The analysis technique presented here uses a fast Fourier transform (FFT) with a computer simulation to allow undesirable nonlinear effects such as amplitude errors and harmonic distortion to be examined. Results of the analysis show that compression can be used to significantly increase dynamic range with only a moderate penalty in overall system linearity.

The following sections describe the concept of amplitude compression and present examples of achievable performance for a particular telemetry system and invertible compression function. Also, considerable attention is devoted to describing the Fourier analysis technique developed for this investigation. In some respects, the technique is more significant than the actual results since the technique provides a convenient tool for analyzing virtually any data compression algorithm.

II. BASIC CONCEPT OF AMPLITUDE DATA COMPRESSION

Amplitude data compression basically consists of amplifying lower amplitude signals more than relatively higher amplitude signals. The compressed signal is expanded later in the system to restore the original amplitude information. The intent of amplitude compression is to extend dynamic range of a system by increasing signal to noise ratios for relatively low amplitude signals. The concept of increasing dynamic range by amplitude compression is illustrated by Figure 1 which displays output versus input relationships for a compressing (nonlinear) gain function as well as for a conventional non-compressing (linear) gain function.

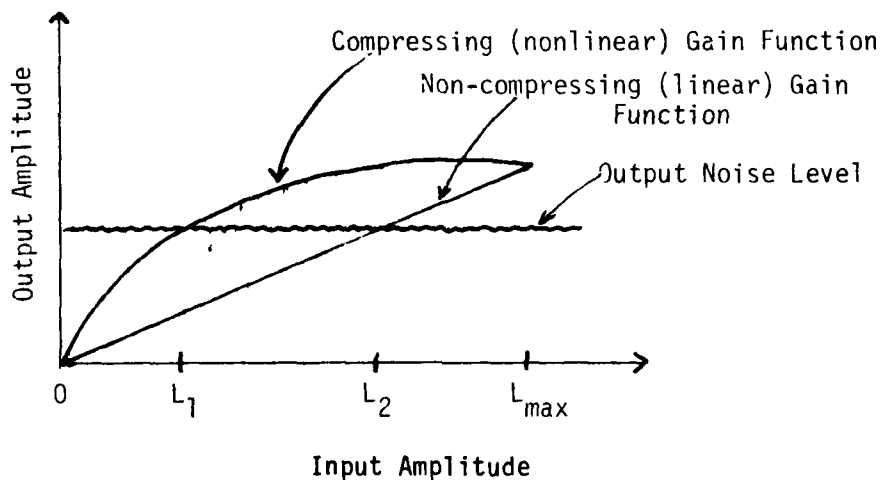


Figure 1. Linear and Nonlinear Gain Functions

Notice from Figure 1 that by compressing the input signal, the output signal amplitude is larger than the output noise level for a wider range of input levels (wider than for a non-compressing gain function).

If we define dynamic range as the ratio of the maximum input signal level to the minimum input signal level (for an output signal to noise ratio = 1), then the dynamic range for the linear (non-compressed) system, D_L , is given by

$$D_L = \frac{L_{\max}}{L_2}$$

Likewise, the dynamic range for the nonlinear (compressed) system, D_{NL} , is given by

$$D_{NL} = \frac{L_{\max}}{L_1}$$

From the example of Figure 1, we see that $L_1 < L_2$ and therefore the dynamic range of the nonlinear system is greater than that of the linear system, viz.

$$D_{NL} > D_L$$

Extending the example of Figure 1, one could choose a compression function to allow a dynamic range as large as desired. Unfortunately, practical problems exist in the inverse, or expanding, process which limit the maximum usable extension of dynamic range. Analysis presented in this technical note examines achievable performance by quantifying detrimental effects such as harmonic distortion and amplitude errors as well as the beneficial effect of extended dynamic range. To proceed with this analysis, it is first necessary to characterize the telemetry system under consideration.

III. VEKA MULTIPLEXED TELEMETRY SYSTEM

A. Linear Configuration

The VEKA telemetry system utilizes frequency division multiplexing (FDM) with the amplitude modulation (AM). Figure 2 displays a simplified single channel model of the telemetry system. The input signal, $s(t)$, is low pass filtered, modulated, transmitted via transmission line, RF link, etc., then demodulated and low pass filtered to obtain an output estimate $\hat{s}(t)$, of the input signal. The low pass filters are included to prevent crosstalk between channels of the frequency division multiplexed system. The additive noise source, $n(t)$, is included to model the telemetry system "mux-demux" noise. This noise is reasonably white (constant power spectral density with respect to frequency) over the frequency band of interest. Noise power in 1 Hz of bandwidth is approximately 80dB below the maximum allowable monochromatic signal level, and therefore, the linear system is described as having 80dB of dynamic range. Amplitude data compression is introduced in the next section.

B. Application of Nonlinear Compression and Expansion

The linear telemetry system model of Figure 2 has been modified to include data compression as shown in Figure 3. Notice from Figure 3 that the *compressor* has been placed *ahead* of the low pass filter. This location (as opposed to after the low pass filter) was selected so that harmonic distortion products from the nonlinear compressor will not result in a rather complicated form of crosstalk in the frequency division multiplexed system. For similar reasons, the expander (inverse of the compressor function) is placed after the low pass filter of the demodulator. At first glance, it may appear that the compression and expansion functions are arranged in a fashion as to exactly cancel each other. This is not true for two reasons: (1) there is a low pass filter operation between the nonlinear operations of compression and expansion, and (2) the signal, $s(t)$, is compressed and expanded whereas the noise, $n(t)$, is expanded only. Closed form characterization of these effects would be extremely difficult due to the nonlinear compression and expansion functions. It is precisely the difficulty of closed form analysis that motivated development of the computer simulation described in the next section.

The *expansion* function (see Figure 3) can be performed in the time domain or the frequency domain. Experiments conducted during the investigation described here indicate both techniques to be satisfactory for high signal to noise ratios. For low signal to noise ratios, however, the frequency domain expansion technique was found to be superior. The expansion operation will be described in more detail later.

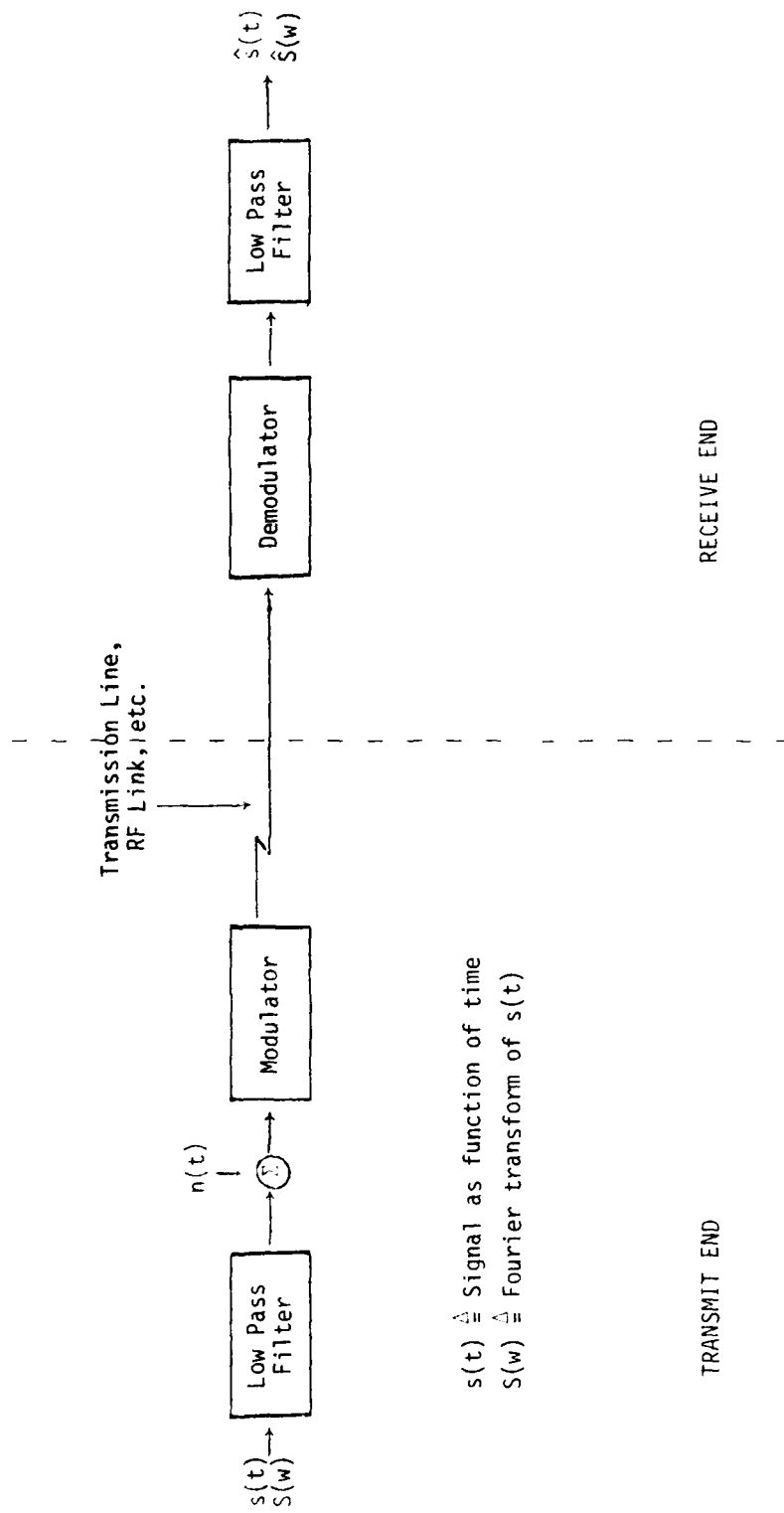
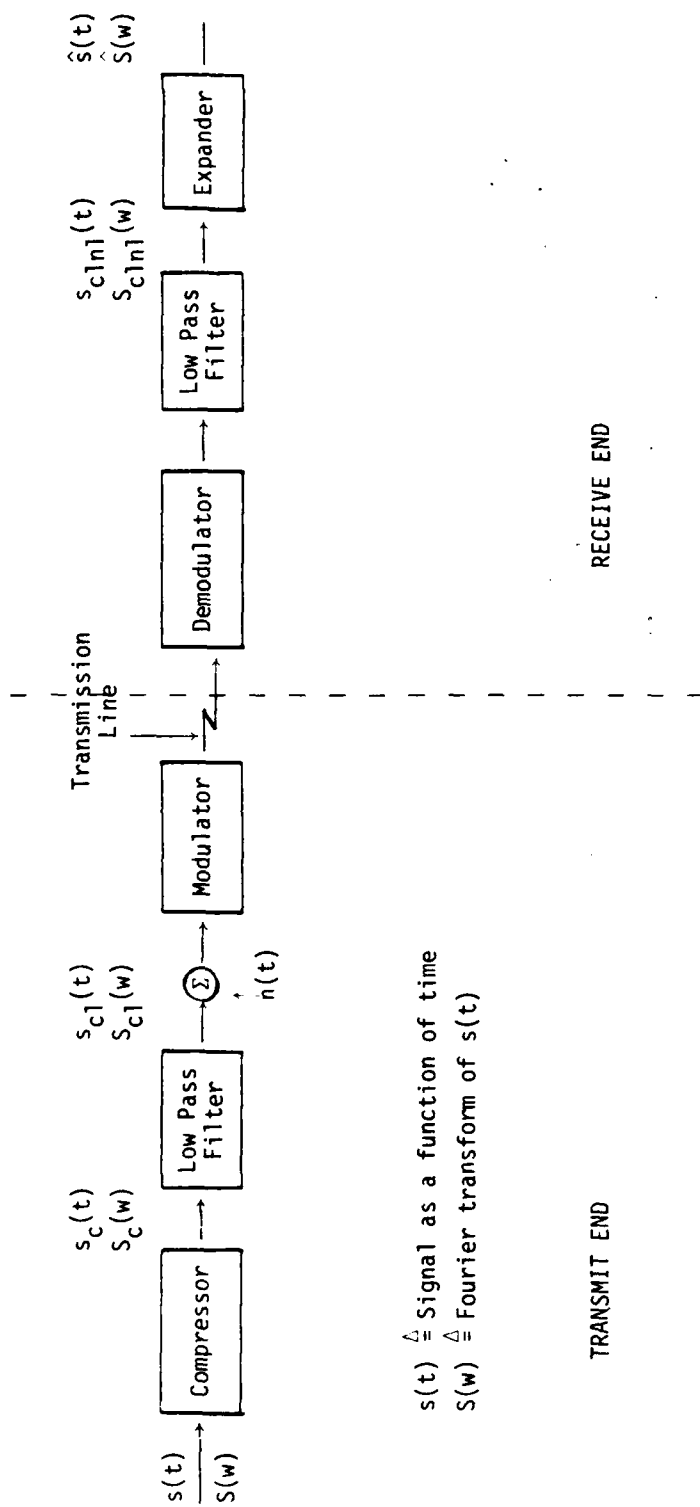


Figure 2. Linear Telemetry System Model



$s(t) \triangleq$ Signal as a function of time
 $S(w) \triangleq$ Fourier transform of $s(t)$

Figure 3. Telemetry System Model with Data Compression

IV. COMPUTER SIMULATION

The computer simulation developed for the effort described here is a numerical technique for evaluating performance of amplitude data compression/expansion algorithms. Performance is quantified by output signal to noise ratio, amplitude errors, and harmonic distortion. The simulation is extremely useful since it provides the necessary information for evaluating compression designs without fabricating expensive hardware prototypes. Also, the simulation is quite versatile which allows evaluation of any compression/expansion functions whereas a closed form analysis, due to the complexity of analyzing nonlinear processes, is limited to a small class of functions.

The software simulates the hardware described in the block diagram of Figure 3. The input signal, $s(t)$, is represented by a sinusoid and is compressed by the desired compression function to generate $s_c(t)$. A fast Fourier transform (FFT) (Cooley, 1965, Bloomfield, 1976) is used to determine the Fourier series representation of $s_c(t)$, denoted by $S_c(w)$. A very fast sample rate (approximately 25 times the highest frequency component of $s(t)$) is used in order to prevent harmonics generated by the compressor from aliasing with significant amplitude into the frequency spectrum of interest. The Fourier representation, $S_c(w)$ allows the low pass filter operation to be performed quite easily as a product in the frequency domain as opposed to a convolution in the time domain. Output of the low pass filter, $s_{cl}(t)$, is added to a pseudo random white noise sequence, $n(t)$, to form $s_{cln}(t)$. The modulator and demodulator are modeled together as an ideal pair, *i.e., the demodulator output is identical to the modulator input. The receive end low pass filter function is then performed to yield $s_{cln1}(t)$.

Expansion can be performed in the time domain or frequency domain. Time domain expansion is performed by operating on the signal $s_{cln1}(t)$ with identically the inverse of the compression function.

Frequency domain expansion is performed by first taking the FFT of s_{cln1} and applying an amplitude correction to each discrete frequency component. The time domain output, $\hat{s}(t)$, can then be generated by inverting the amplitude corrected FFT of s_{cln1} . In either case, time domain expansion or frequency domain expansion, system performance is evaluated by comparing the FFT of the output $\hat{S}(w)$ with that of the input $S(w)$.

V. RESULTS

The results presented here were obtained using the simulation described in the previous section. A linear (uncompressed) telemetry model was designed to approximate characteristics of the current NORDA VEKA telemetry system. In particular, the linear telemetry model was designed to simulate 80dB of dynamic range, where dynamic range, DR, is defined as the ratio (max monochromatic RMS signal level/RMS noise level in 1Hz of bandwidth). To model the 80dB dynamic range, pseudo random noise source, $n(t)$, was set to -80dB amplitude in 1Hz bandwidth and the input signal amplitude was constrained to 0dB.

- * The non-ideal nature of the pair (with transmission line) is accounted for by additive noise source $n(t)$ and a maximum input level "clipping" limit.

The particular compression function used here was chosen by intuition and in no way represents an optimum choice. The compression function used, however, does demonstrate the feasibility of achieving an extra 40dB (80dB to 120dB) of dynamic range when applied to the current VEKA telemetry system. Before detailed results can be presented in a meaningful fashion, several more modeling assumptions must be described.

A. Compression Function

The compression function is designed to "compress" an input signal amplitude range to a smaller output signal amplitude range. The particular compression function used here is shown below.

$$s_c(t) = f_c(s(t)) = \alpha s(t) + \eta(|s(t)|)^{\frac{1}{2}} \text{SGN}(s(t)) \quad (1)$$

Where $s(t) \triangleq$ input (uncompressed) signal as a function of time, t ,

$f_c \triangleq$ compression function,

$s_c(t) \triangleq$ output (compressed) signal as a function of time,

$\alpha = 0.9$,

$\eta = 0.14$,

$|X|$ = denotes absolute value of X and

$\text{SGN}(X) = +1$, for $X \geq 0$

$= -1$ otherwise.

The particular values for α and η were chosen to compress a 120dB range to approximately 80dB range. Figure 4 describes the compression function by plotting s_c as a function of s for positive s . An identical curve (except for signs) would describe s_c and s for negative s . Figure 5 also describes the compression function input output relationship. Figure 5 was generated by assuming a sinusoidal compressor input

$$s(t) = A_1 \sin(w_0 t) \quad (2)$$

which results in a non-sinusoidal compressor output which may be expressed by

$$s_c(t) = f_c(s(t)) = B_1 \sin(w_0 t) + \sum_{n=2}^{\infty} B_n \sin(nw_0 t) \quad (3)$$

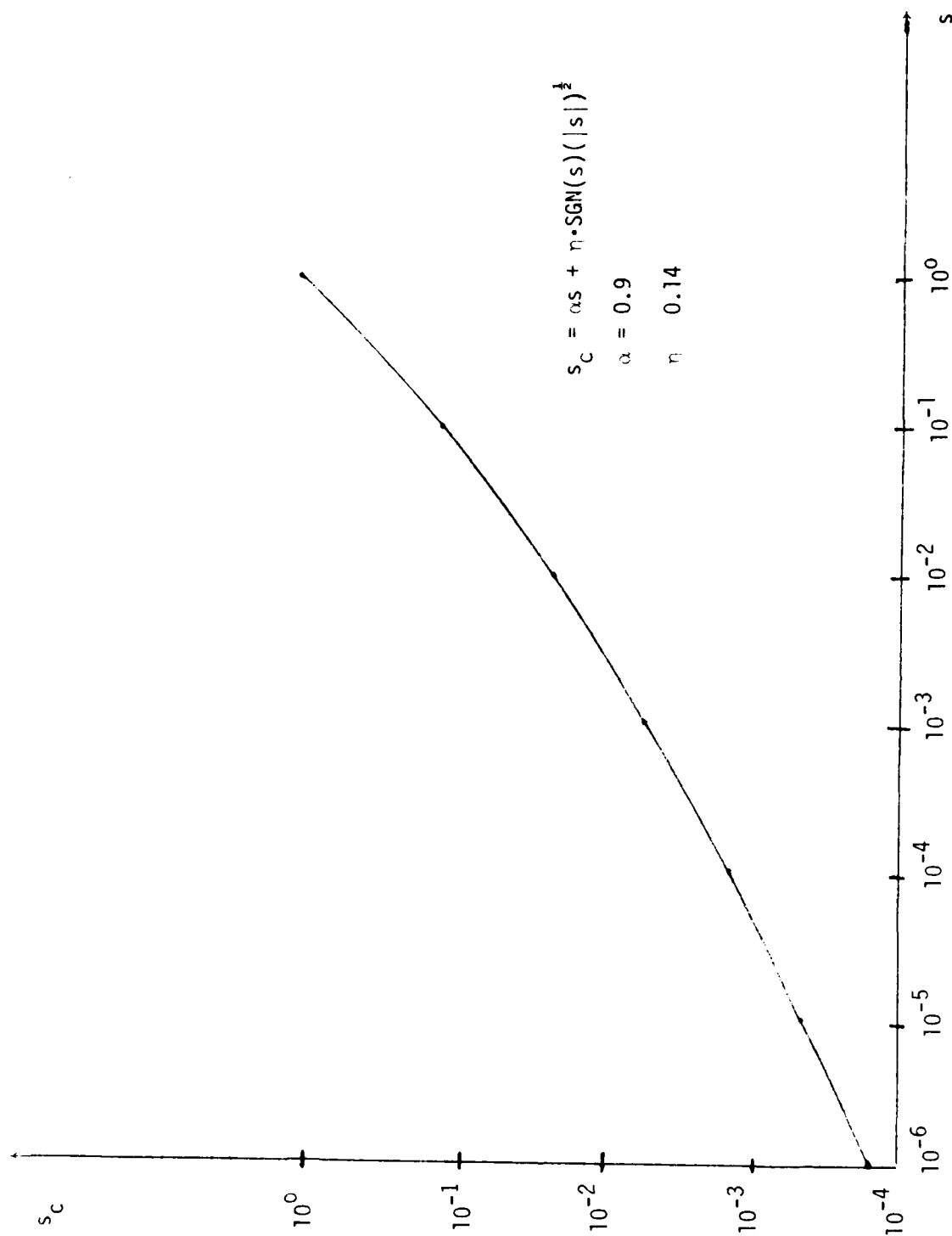


Figure 4. Compressor Output Magnitude versus Compressor Input Magnitude

Figure 5 displays coefficient B_1 of equation (3) as a function of coefficient A_1 of equation (2). In other words, Figure 5 displays magnitude* of the output at the frequency of the sinusoidal input as a function of the magnitude* of the sinusoidal input. Notice from Figure 5 that a sinusoidal input of magnitude -120dB results in an output (at the fundamental frequency) of -79dB. Also, notice that an input of 0dB results in an output of 0dB. Therefore, the input range of 120dB has been compressed to approximately 80dB.

B. Time Domain Expansion

Time domain expansion is performed by exercising the inverse of the compression function. The inverse, or expansion function, f_e is given by

$$s = f_e(s_c) = \left(\frac{-n + (n^2 + 4\alpha |s_c|)^{\frac{1}{2}}}{2\alpha} \right)^2 \text{SGN}(s_c). \quad (4)$$

where terms and notation are defined in equation (1). Under conditions of no noise and no filtering (between compressor and expander), the compression and expansion functions form an ideal pair, viz.

$$s \equiv f_e(f_c(s)), \text{ for all } s. \quad (5)$$

Intuitively, the actual inverse function, f_e , would be the optimum algorithm for expanding the compressed data. In the presence of noise, however, the frequency domain expansion has been found to be superior (in terms of output signal to noise ratio) to time domain expansion.

C. Frequency Domain Expansion

Frequency domain expansion is performed by first taking the fast Fourier transform (FFT) of the received output (s_{c1n} of Figure 3) and then applying an amplitude dependent amplitude correction factor to each Fourier component. The time domain version of the expanded signal can be obtained by inverting the amplitude corrected FFT. The amplitude dependent amplitude correction factor is obtained from Figure 5.

As an example, consider the input signal $s(t)$ sinusoidal of magnitude -80dB. From Figure 5, we see that the output magnitude (at frequency of $s(t)$) of the compressor is -58.5dB. The compressed signal is then low pass filtered, etc. The resulting signal ($s_{c1n}(t)$ of Figure 3) will have a spectral component (at the frequency of $s(t)$) very nearly -58.5dB.** Applying the frequency domain expansion correction factor, results in the approximately -58.5dB level to be mapped to approximately -80dB.

* Input and output magnitudes are expressed in dB relative to unity RMS. As an example $A_1 = (2)^{\frac{1}{2}}$ is equivalent to $s(t)$ of 0dB.

** Signal $s_{c1n}(t)$ will have a magnitude slightly different from -58.5dB due to additive noise $n(t)$.

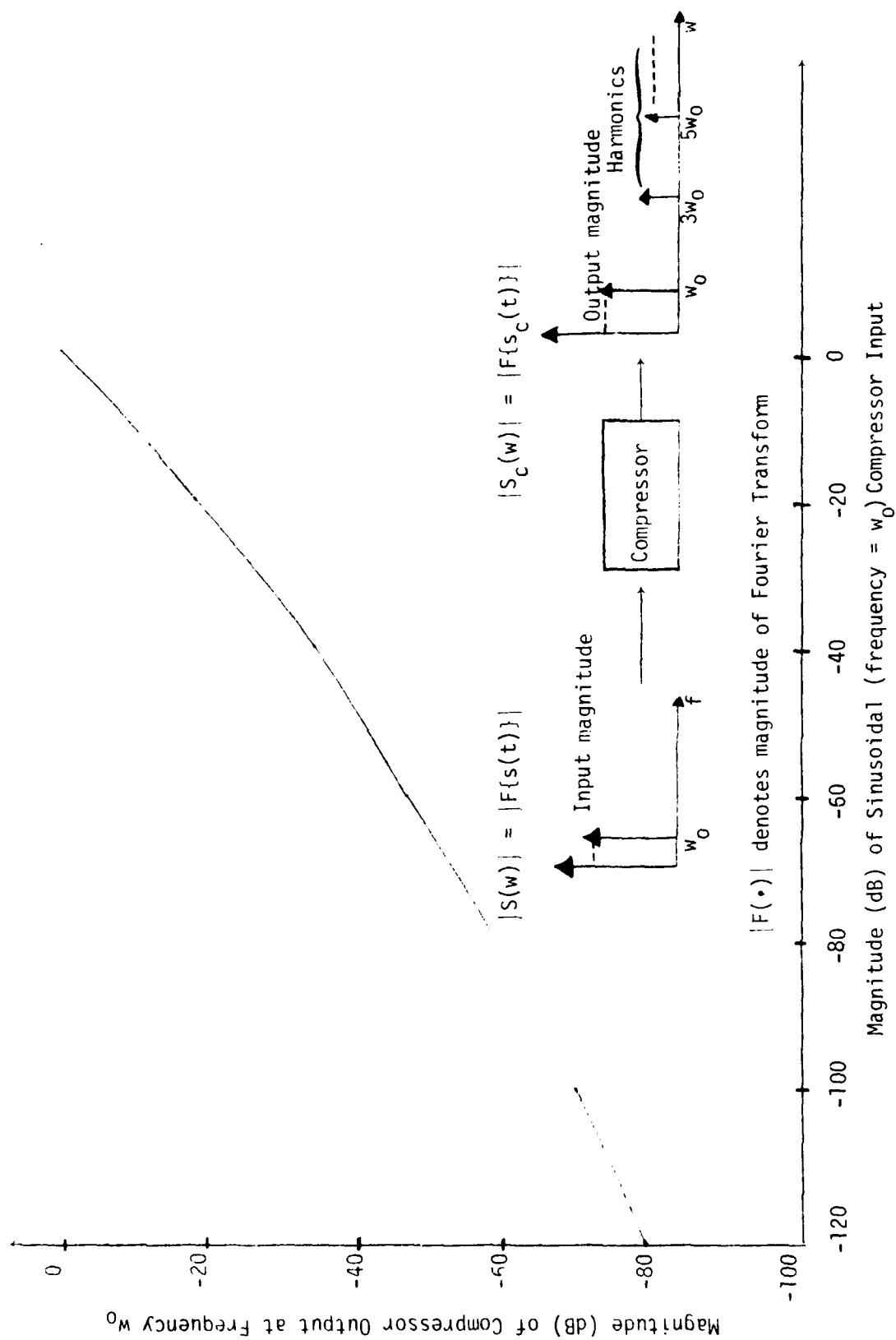


Figure 5. Compressor Output Versus Compressor Input for Sinusoidal Input

D. Low Pass Filtering

Low pass filters are assumed linear phase with infinitely sharp cutoff as illustrated by the transfer function shown below.

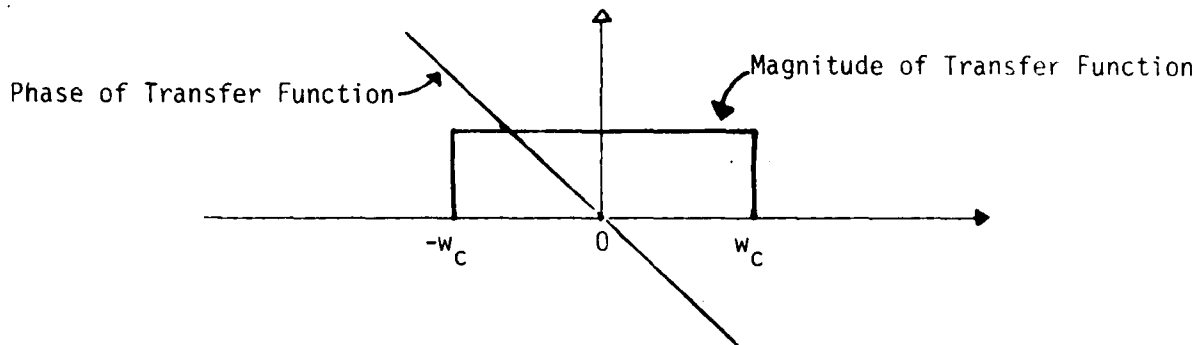


Figure 6. Ideal Low Pass Filter Characteristics

These ideal characteristics were assumed for simplicity and result in no significant shortcoming of the analysis.

E. Examples

The examples presented here are intended to illustrate the signal characteristics at various stages of the telemetry system and to illustrate how overall performance is evaluated using the computer simulation. An example of high signal level and low signal level will be presented.

Example 1: (high signal level)

The highest allowable* sinusoidal signal level corresponds to 0dB for $s(t)$ of Figure 7a. Figure 7b shows the magnitude Fourier transform of the input signal $s(t)$, denoted by $S(w)$. The "compressed" version of $s(t)$, denoted by $s_c(t)$, contains harmonics as well as the fundamental and is characterized by the magnitude transform, $S_c(w)$ shown in Figure 7c. In this example, it is assumed the frequency, w_0 , of the sinusoidal input signal is *very much less* than the low pass filter cutoff frequency, w_c . Therefore, virtually all the harmonic components of $s_c(t)$ are transmitted to the receive end telemetry. Pseudo random white noise (represented by $n(t)$ of Figure 7a) is added to the compressed and low pass filtered signal $s_c(t)$. After receive end low pass filtering, the signal, $s_{clp}(t)$ has a magnitude Fourier transform as shown in Figure 7d. Time domain expansion (TDE) is performed by exercising equation 4. Figure 7e characterizes the time domain expanded signal by plotting its magnitude Fourier transform, $S_{TDE}(w)$. Notice that harmonic distortion of the time domain expanded signal is not visible above the noise. Frequency domain expansion

* Highest level that "clipping" does not occur.

(FDE) results in the signal whose magnitude transform is shown in Figure 7f. Notice the noise level of Figure 7f (FDE) is -122dB as opposed to -79dB for Figure 7e (TDE). Also, notice the largest harmonic distortion term of the FDE signal is 43dB below the fundamental (as opposed to > 70dB for the time domain expanded (TDE) signal). To summarize, the improved signal to noise ratio of FDE (over TDE) has been achieved at the expense of poorer linearity which results in higher harmonic distortion.

Example: (low level signal)

A signal level of -80dB represents the case where output signal to noise ratio is 0dB for the conventional linear (uncompressed) telemetry system. Figures 8a and 8b display the magnitude Fourier transform of the input signal, $S(w)$, and the compressed signal, $S_c(w)$. Figures 8d and 8e characterize the signals after time domain expansion (TDE) and frequency domain expansion (FDE). Notice that both expansion techniques perform quite well in that the output signal to noise ratio is much better than the 0dB of the original linear system. Also, notice the signal to noise ratio is much better (approximately 42dB S/N as opposed to approximately 18dB S/N) for the frequency domain expanded signal as opposed to the time domain expanded signal.

F. Performance for Signals of Magnitude 0dB to -90dB

The data presented here is in a format very similar to that of the previous two examples. A major difference is that two frequencies are considered for $s(t)$. The two frequencies do not occur simultaneously, but are considered in separate experiments. The first frequency is a *low* frequency which allows virtually *all* the harmonic information from the compressor to be telemetered to the expander. The second frequency considered is a *high* frequency which allows *none** of the harmonic information from the compressor to be telemetered to the expander. The low frequency signal was selected to allow observation of the intuitively worse case for harmonic distortion appearing in the output signal, \hat{s} . The high frequency was selected to demonstrate the worse case *loss of harmonic information* between the compressor and expander.* This loss of harmonic information affects time domain expansion.

Figures 9a-9j characterize performance of the linear (uncompressed) system and the amplitude compressed system using time domain expansion (TDE) and frequency domain expansion (FDE). Figures 9a-9j consider a low frequency sinusoidal input as discussed in the just previous paragraph. Notice that for signal amplitudes greater than -60dB all systems, including the standard linear system, perform very well with respect to three criteria. (1) output signal amplitude is very nearly the same as input signal amplitude, (2) output signal to noise ratio is large, and (3) harmonic distortion terms are typically better than 30dB below the amplitude of the fundamental signal. For signal levels less than -60dB, the signal to noise ratio of the linear telemetry system becomes small. Signal to noise ratios for the compressed system using time domain expansion is greater than that of the linear system and signal to noise ratios

* Harmonics of high frequencies are removed by the low pass filtering.

for the compressed system using frequency domain expansion are even greater. The enhanced signal to noise ratio of the FDE system is achieved at the expense of greater harmonic distortion. An interesting property of the compressed system using time domain expansion is that output noise amplitude is a function of signal amplitude.

Figures 10a-10j describe performance characteristics of the system for a high frequency signal. The significance of the "high" frequency is that the low pass filtering removes all harmonic components of the compressed signal. The harmonic information is necessary to reconstruct the input signal exactly. Therefore, it is interesting to observe signal degradation due to loss of harmonic information. The experimental results presented in Figures 10 indicate the degradation insignificant for the cases investigated.

G. Performance for Signals of Magnitude -100dB to -110dB

Performance of the systems for sinusoidal signals of -100dB and -110dB magnitude were evaluated by averaging the results of 32 trials (experiments). The averaging was necessary to obtain a better estimate of the output signal to noise ratios. Performance of the linear system is very poor for the low level signals and, therefore, is not displayed. Figures 11a and 11b illustrate performances of the amplitude compressed systems using time domain expansion (TDE) and frequency domain expansion (FDE). Again, $S(w)$ denotes Fourier transform of input signal and $\hat{S}(w)$ denotes Fourier transform of output signal. Notice the amplitude accuracy and output signal to noise ratio of FDE signal is better than that of the time domain expanded (TDE) signal.

H. Summary of Results

The amplitude data compressed telemetry system achieved a dynamic range of approximately 105dB using time domain expansion and approximately 120dB using frequency domain expansion. These dynamic ranges were achieved by applying amplitude data compression to a linear telemetry system of 80dB dynamic range. Dynamic range was defined as the ratio (max RMS monochromatic signal level/RMS noise level in 1 Hz bandwidth). Results presented here consider only monochromatic input signals.

VI. CONCLUSIONS AND RECOMMENDATIONS

Results of the analysis presented here show the feasibility of extending the dynamic range of an 80dB system, such as the current NORDA VEKA telemetry, to approximately 120dB. The resulting harmonic distortion is well within performance goals for a practical telemetry system.

The following areas should be explored to continue the theoretical investigation and prepare for hardware implementation.

- Evaluation of system performance for non-monochromatic signals
- More precise modeling of telemetry hardware

- Analysis of frequency domain expansion versus time domain expansion
- Evaluation of phase distortion
- Optimization of compression/expansion functions with respect to system performance and hardware implementation

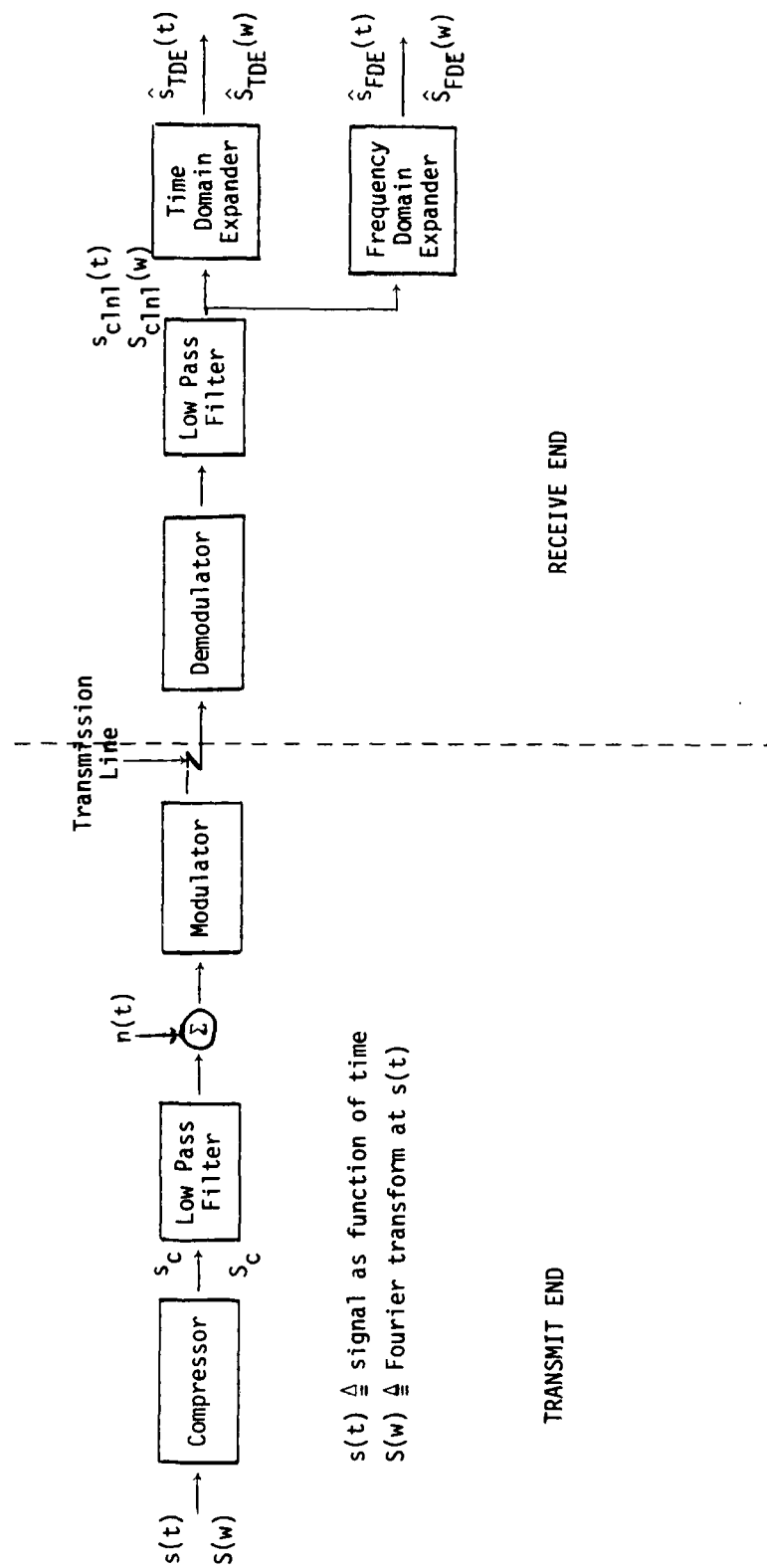


Figure 7a. Telemetry System with Amplitude Compression

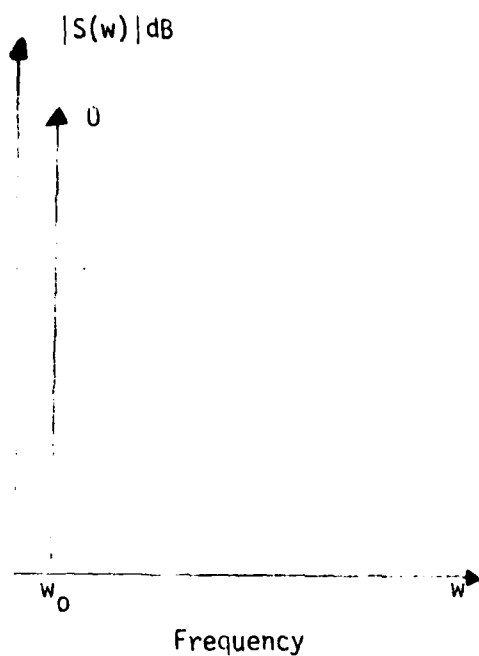


Figure 7b. Magnitude Transform of Input Signal

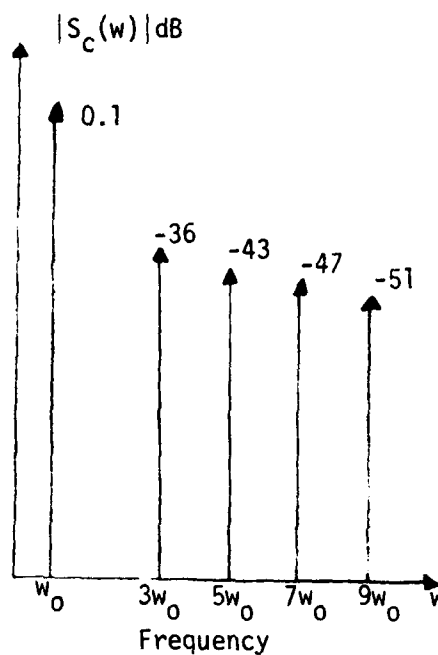


Figure 7c. Magnitude Transform of Compressed Signal

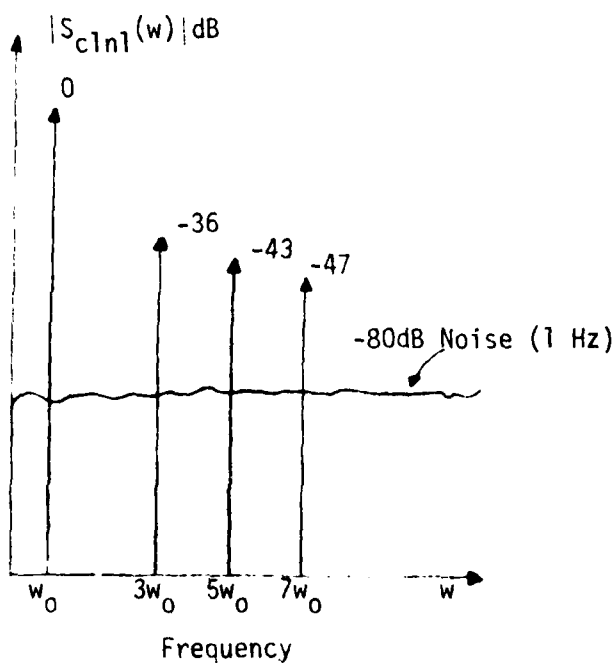


Figure 7d. Magnitude Transform of Receive Signal before Expansion

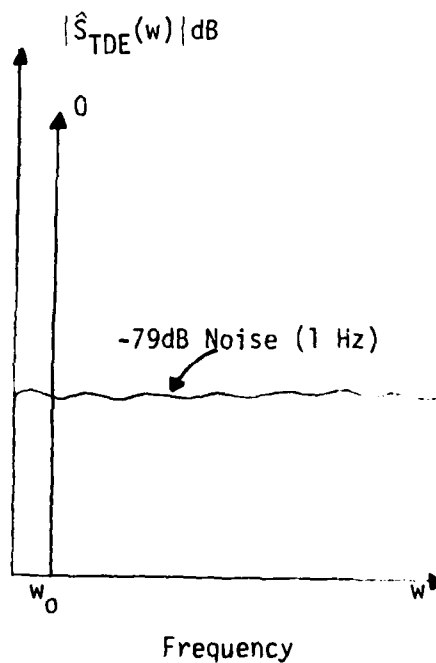


Figure 7e. Magnitude Transform of Time Domain Expanded (TDE) Signal

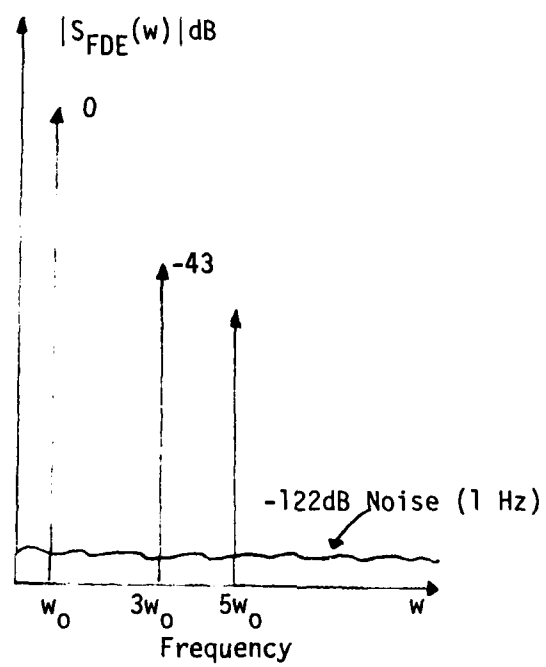


Figure 7f. Magnitude Transform
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Expanded (FDE) Signal

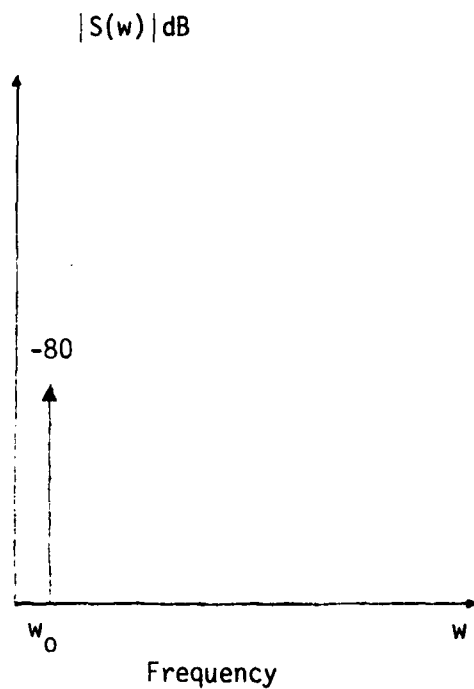


Figure 8a. Magnitude Transform of Input Signal

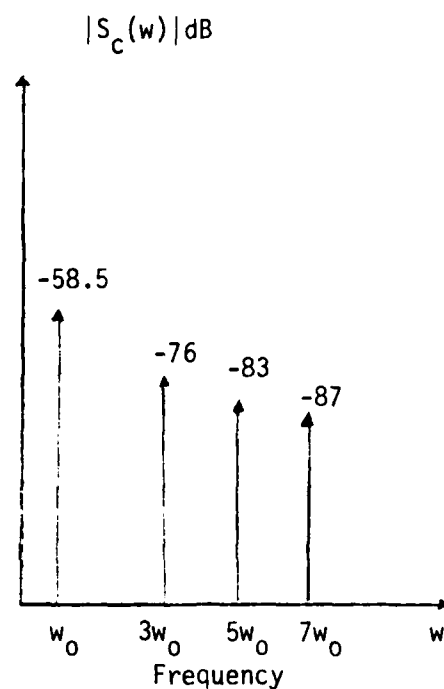


Figure 8b. Magnitude Transform of Compressed Signal

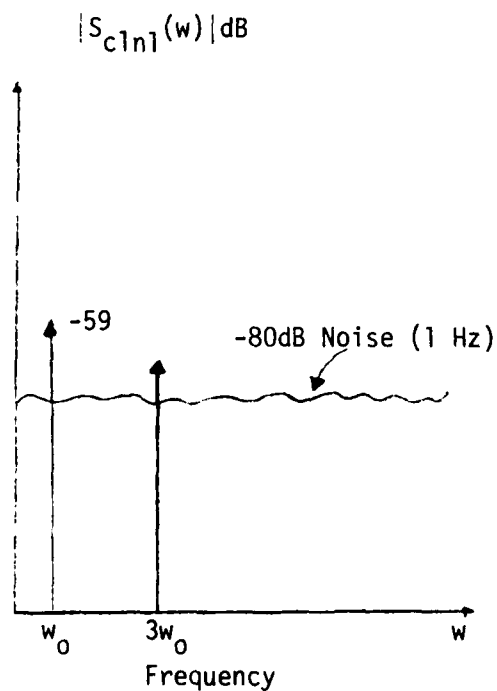


Figure 8c. Magnitude Transform of Received Signal before Expansion

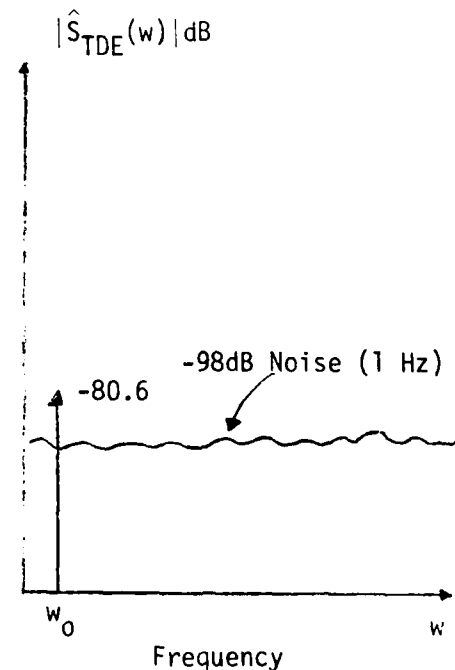


Figure 8d. Magnitude Transform of Time Domain Expanded (TDE) Signal

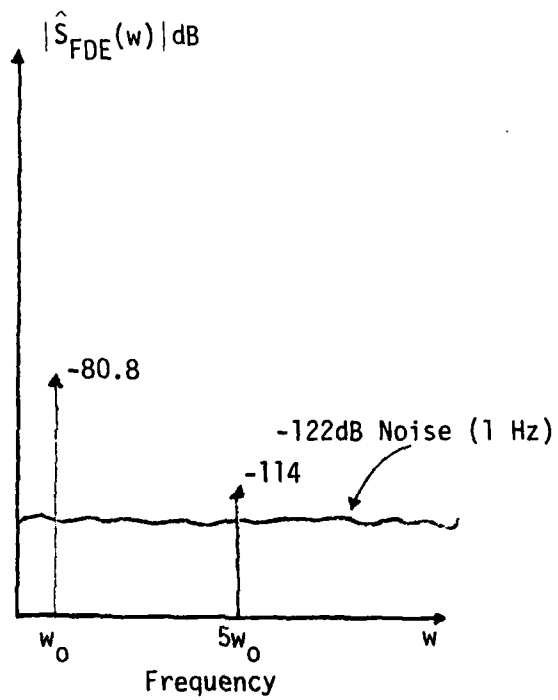


Figure 8e. Magnitude Transform
of Frequency Domain
Expanded (FDE) Signal

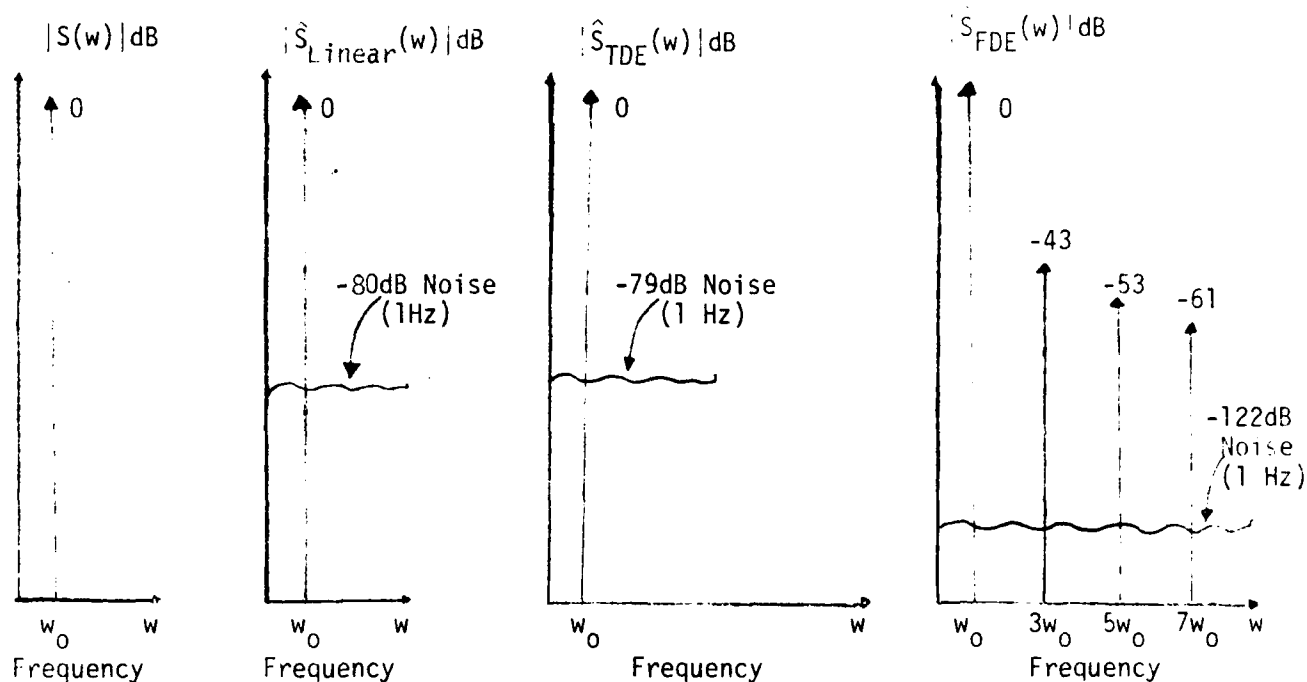


Figure 9a. Systems Performance with Low Frequency 0dB Magnitude Input Signal

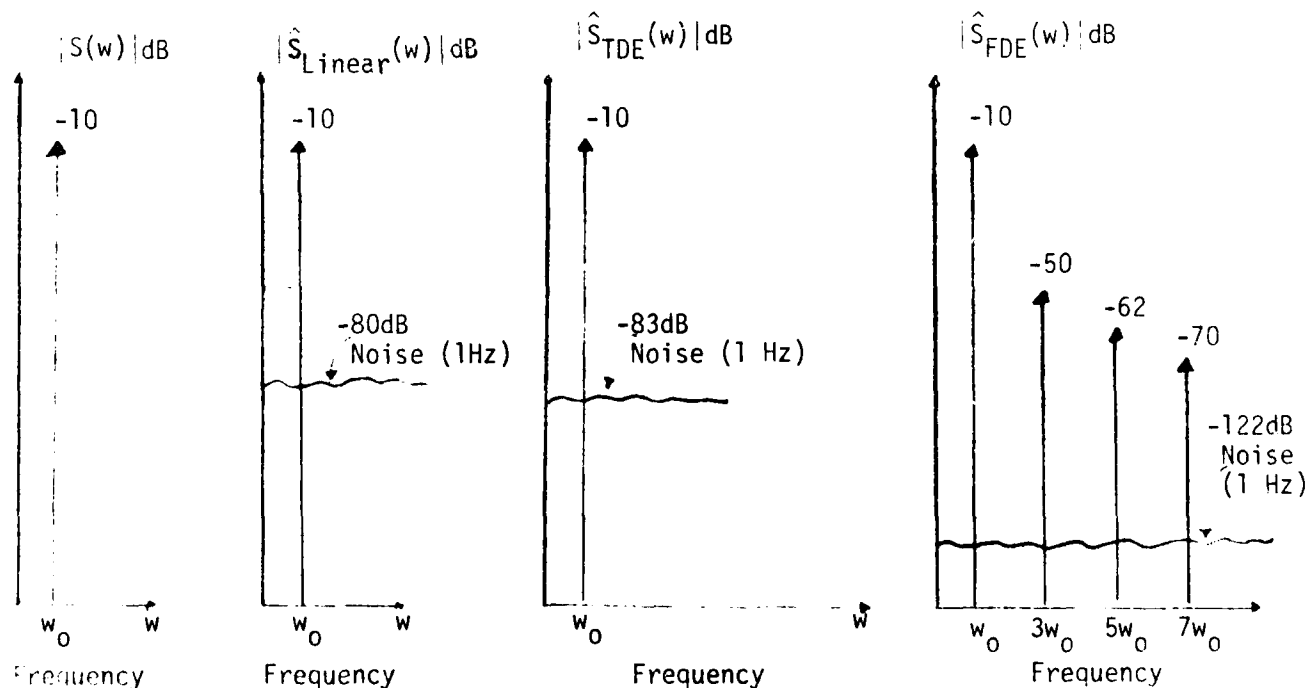


Figure 9b. Systems Performance with Low Frequency -10dB Magnitude Input Signal

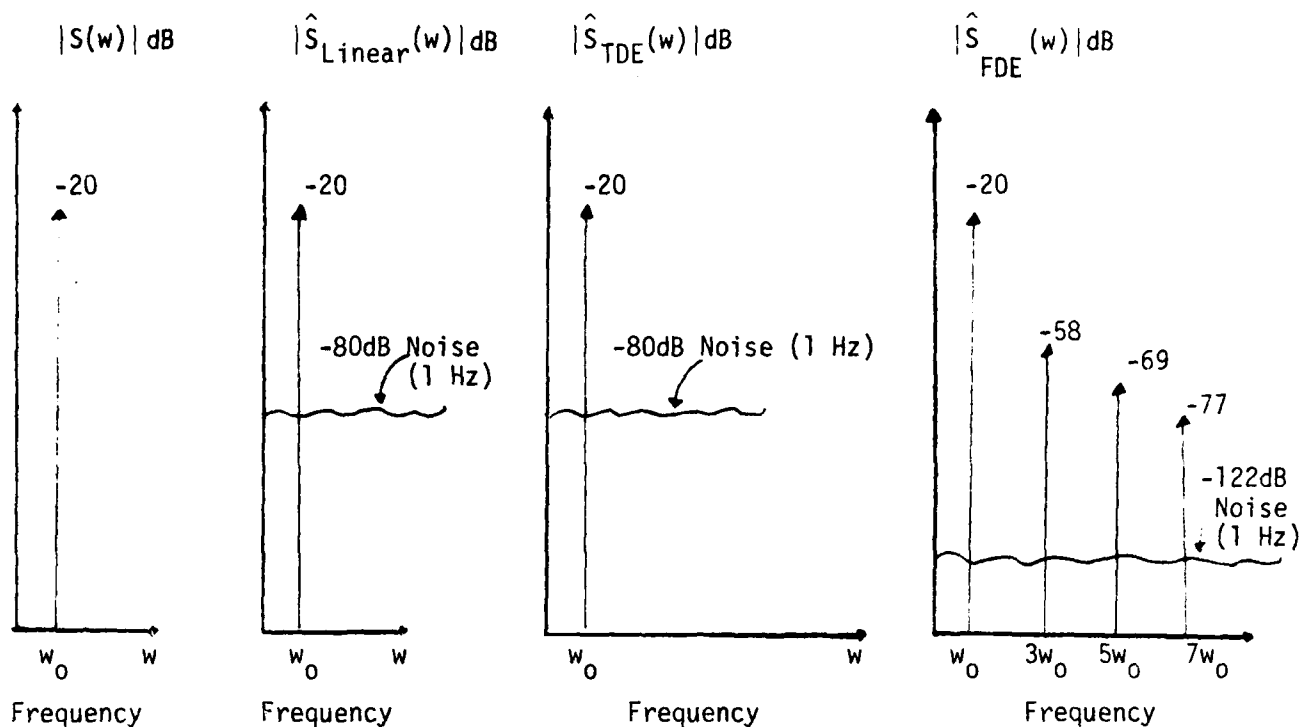


Figure 9c. Systems Performance with Low Frequency -20dB Magnitude Input Signal

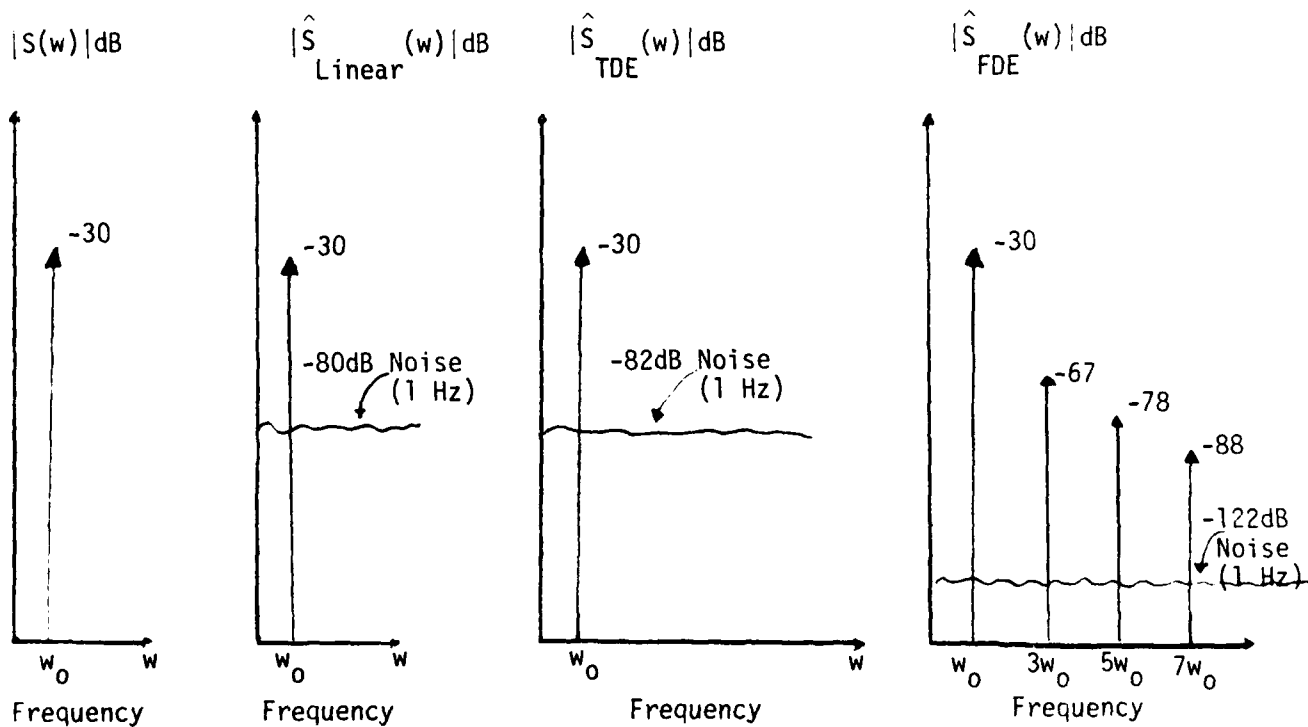


Figure 9d. Systems Performance with Low Frequency -30dB Magnitude Input Signal

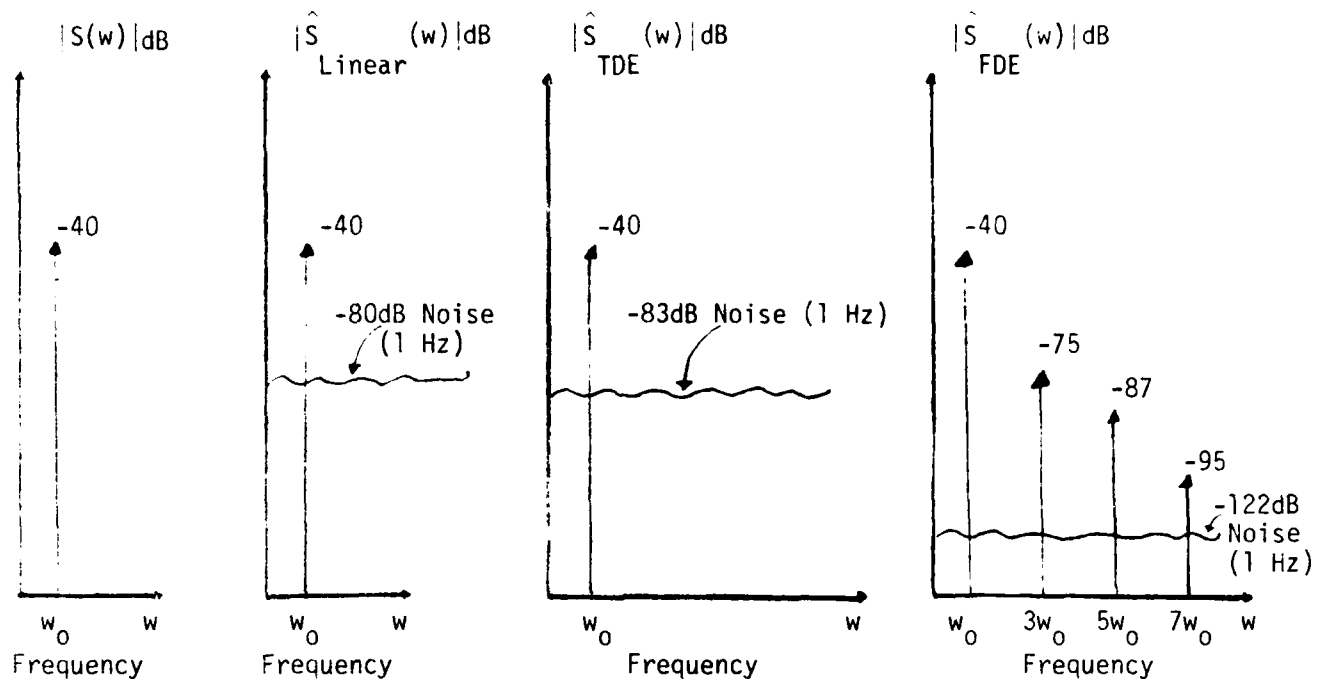


Figure 9e. Systems Performance with Low Frequency -40dB Magnitude Input Signal

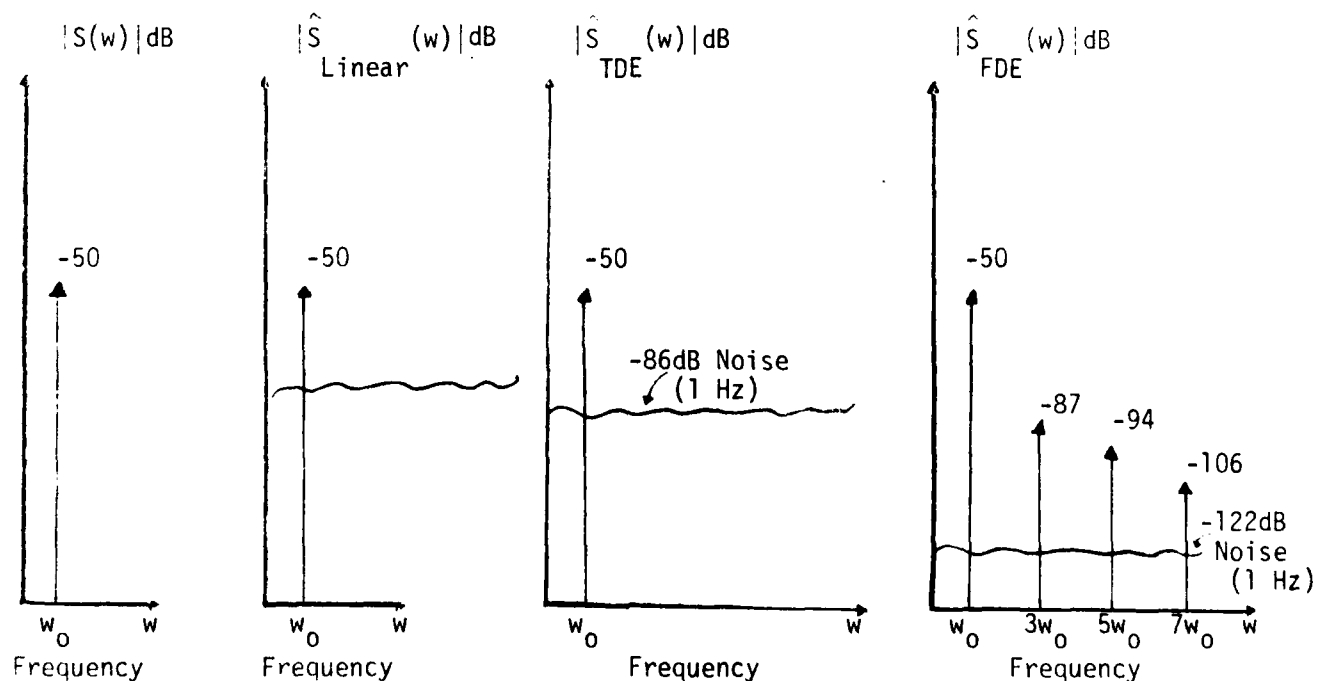


Figure 9f. Systems Performance with Low Frequency -50dB Magnitude Input Signal

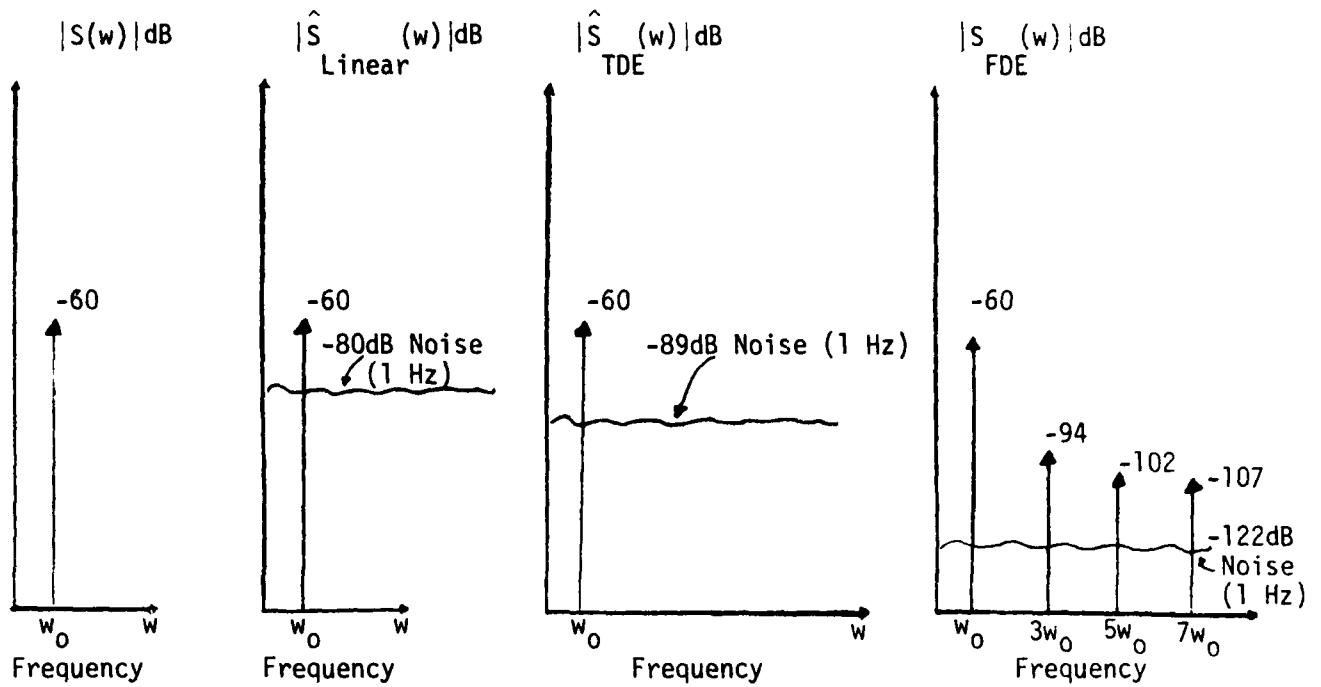


Figure 9g. Systems Performance with Low Frequency -60dB Magnitude Input Signal

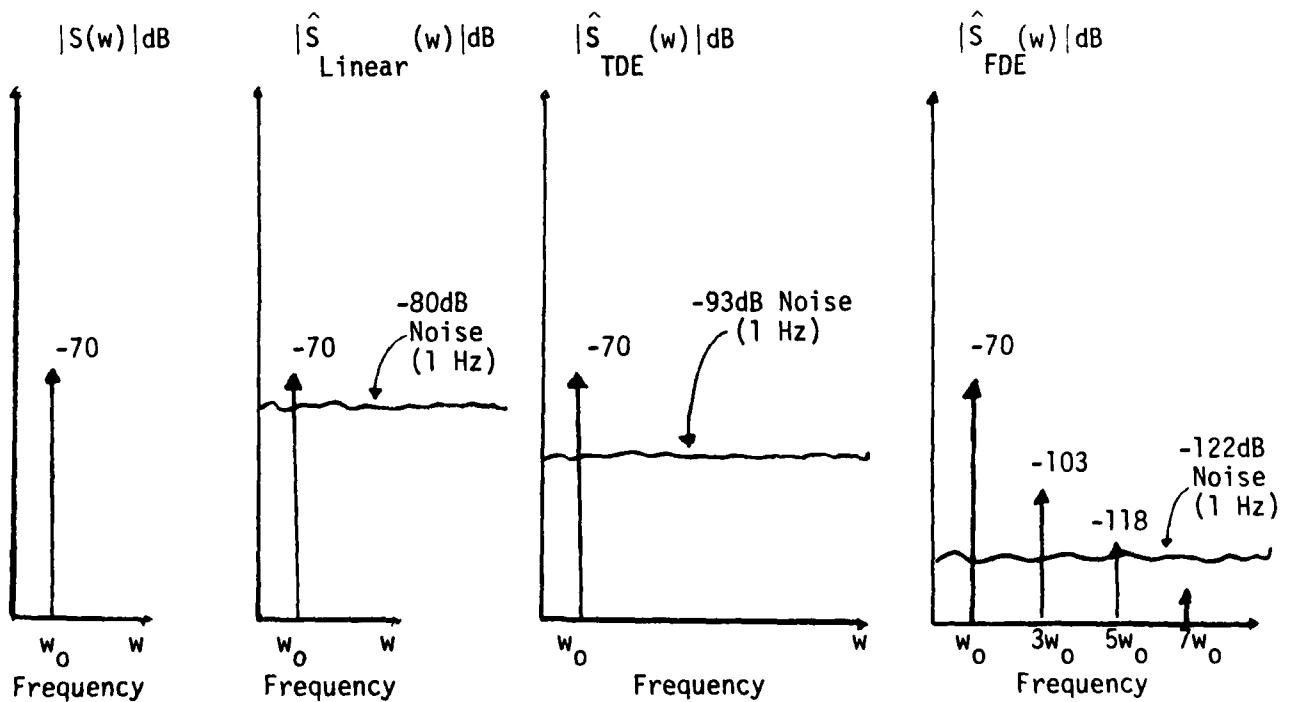


Figure 9h. Systems Performance with Low Frequency -70dB Magnitude Input Signal

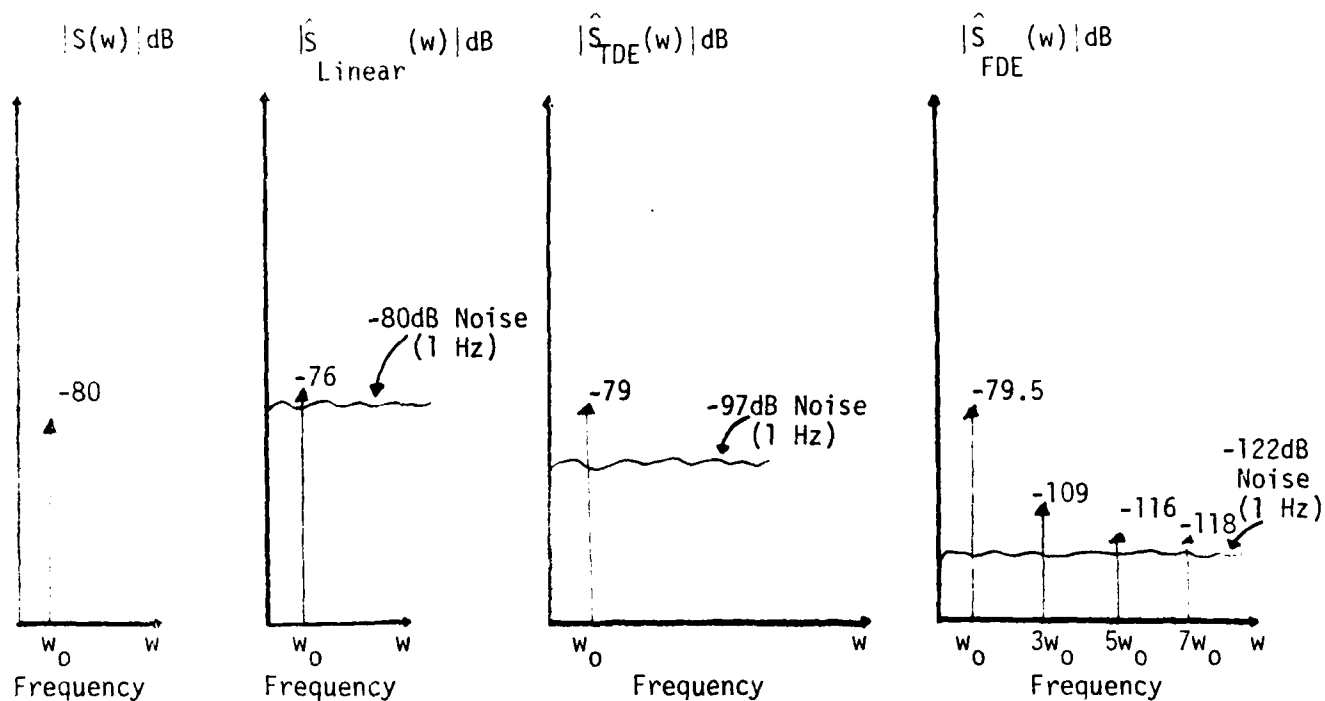


Figure 9i. Systems Performance with Low Frequency -80dB Magnitude Input Signal

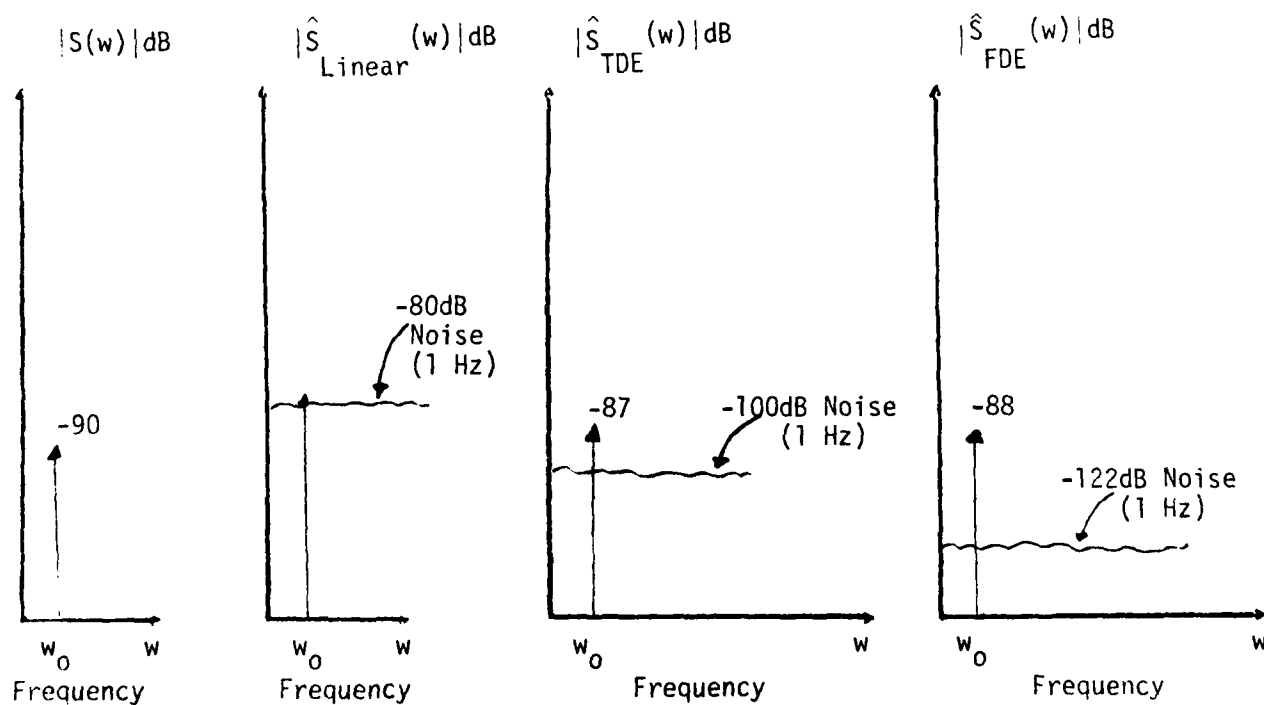


Figure 9j. Systems Performance with Low Frequency -90dB Magnitude Input Signal

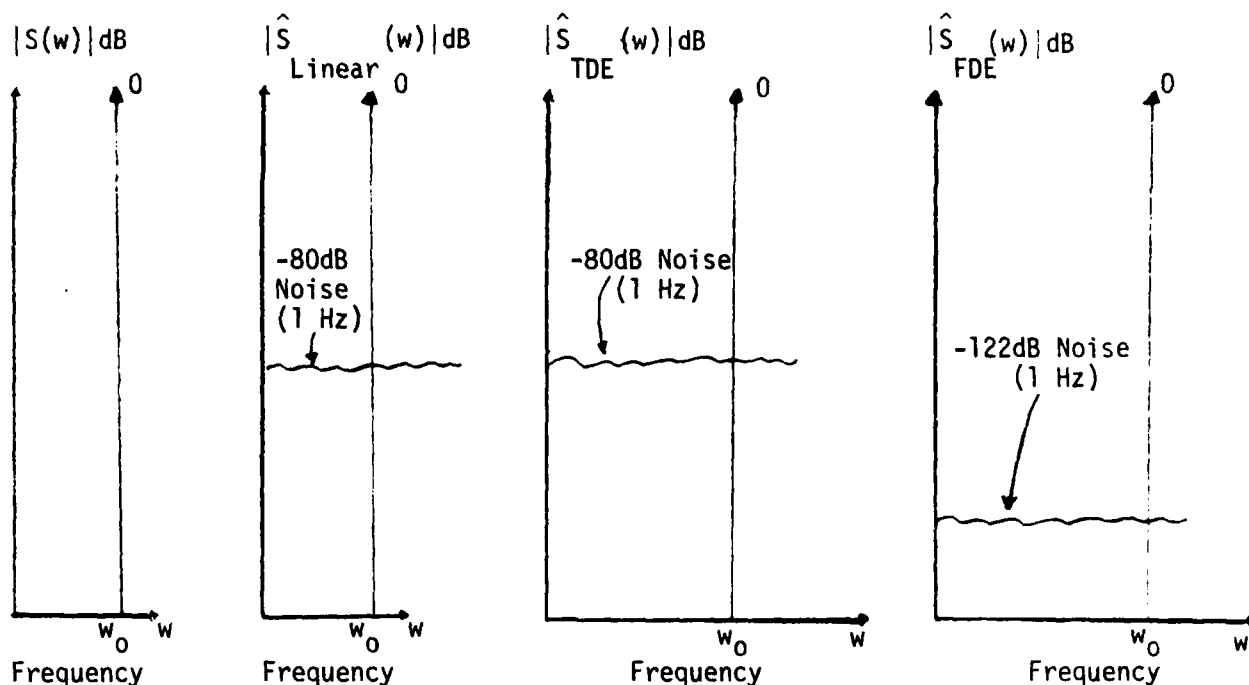


Figure 10a. Systems Performance with High Frequency 0dB Magnitude Input Signal

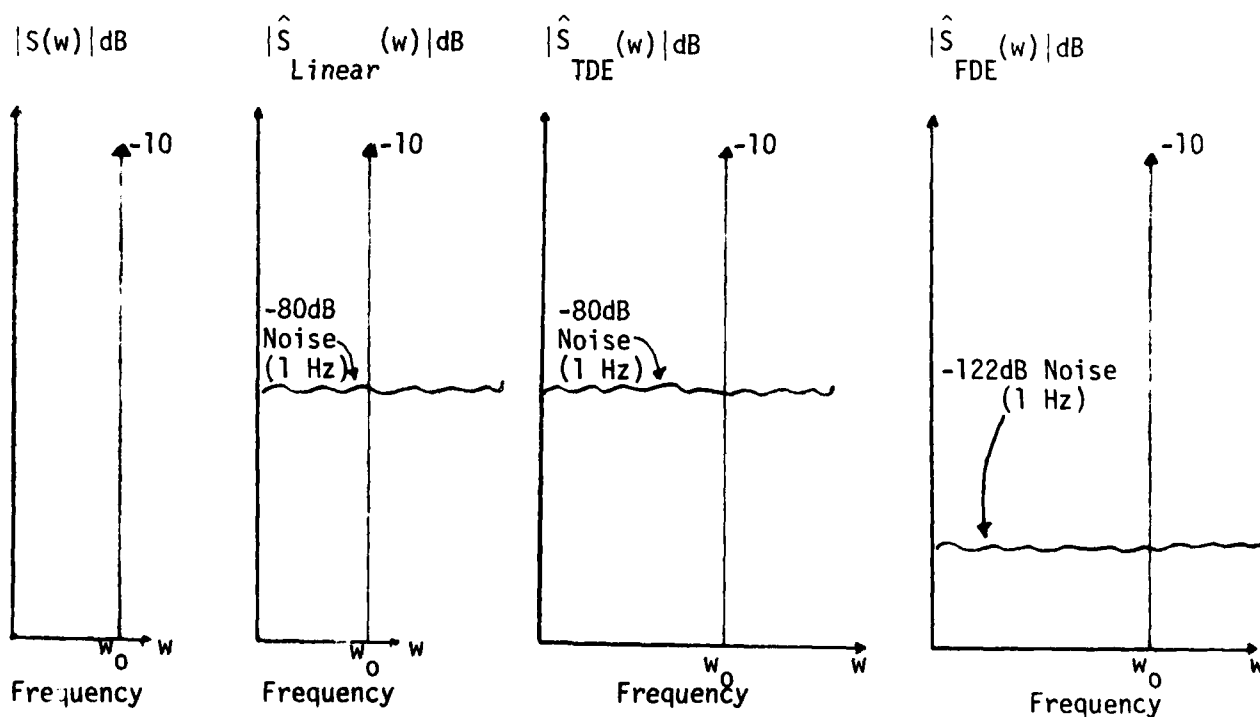


Figure 10b. Systems Performance with High Frequency -10dB Magnitude Input Signal

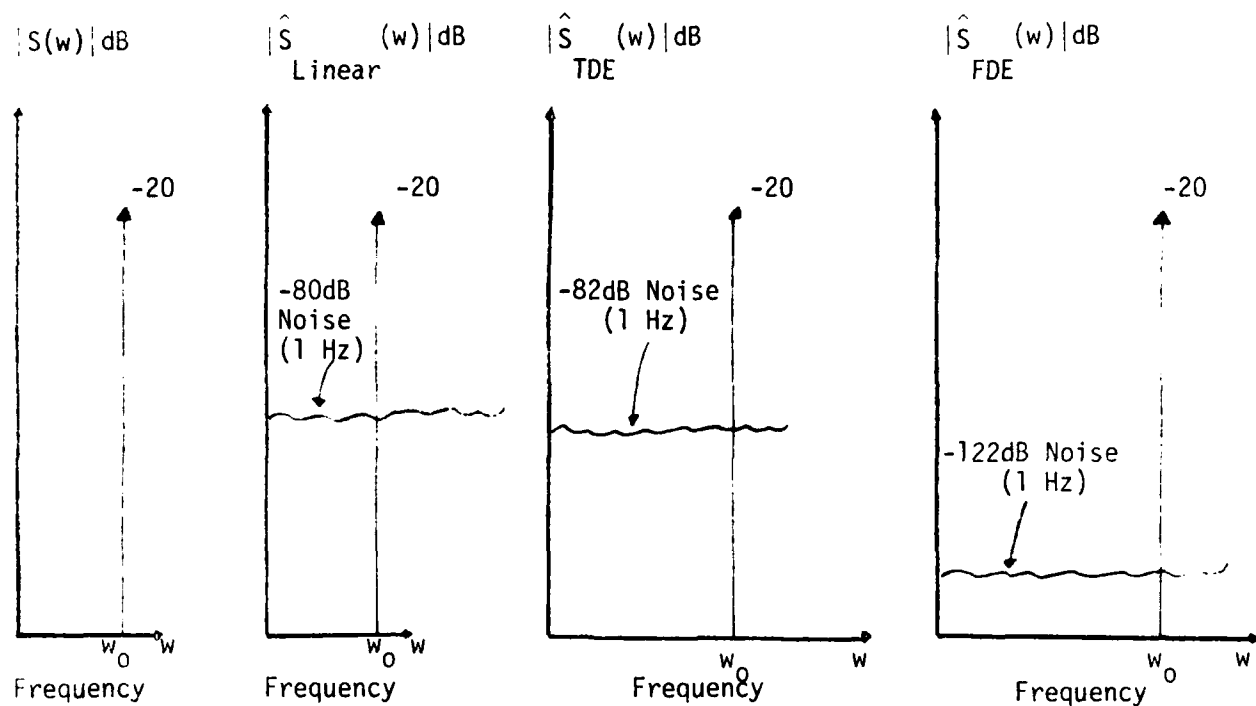


Figure 10c. Systems Performance with High Frequency -20dB Magnitude Input Signal

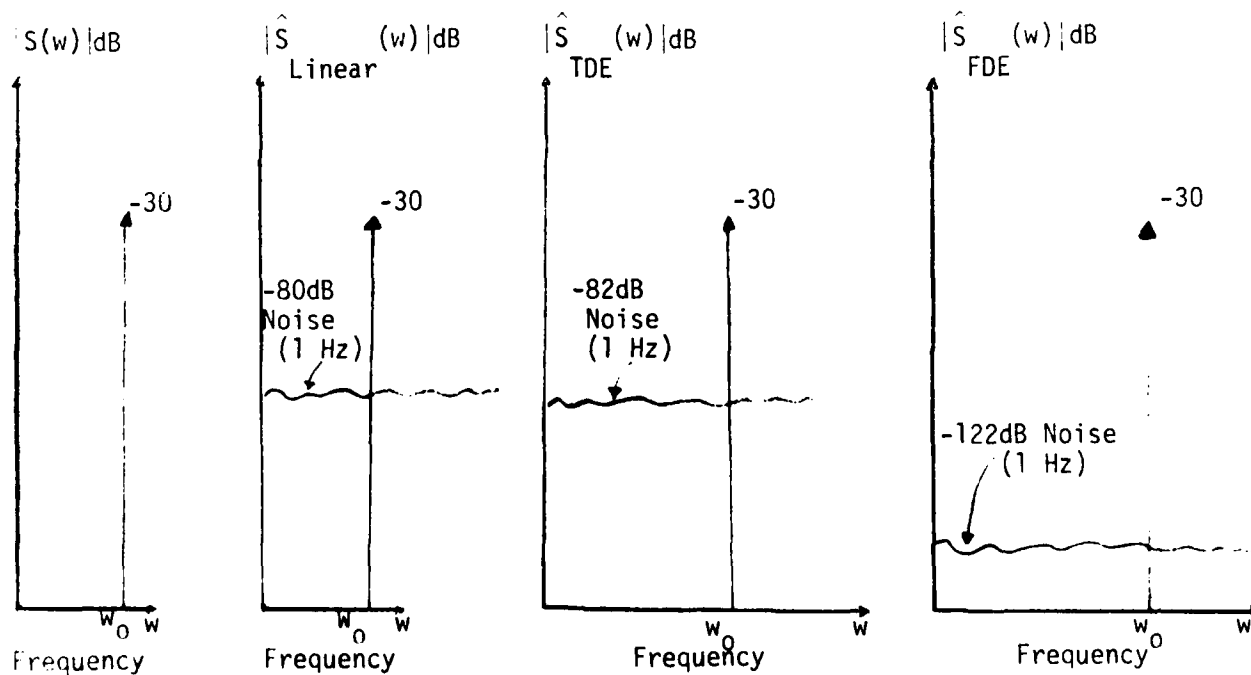


Figure 10d. Systems Performance with High Frequency -30dB Magnitude Input Signal

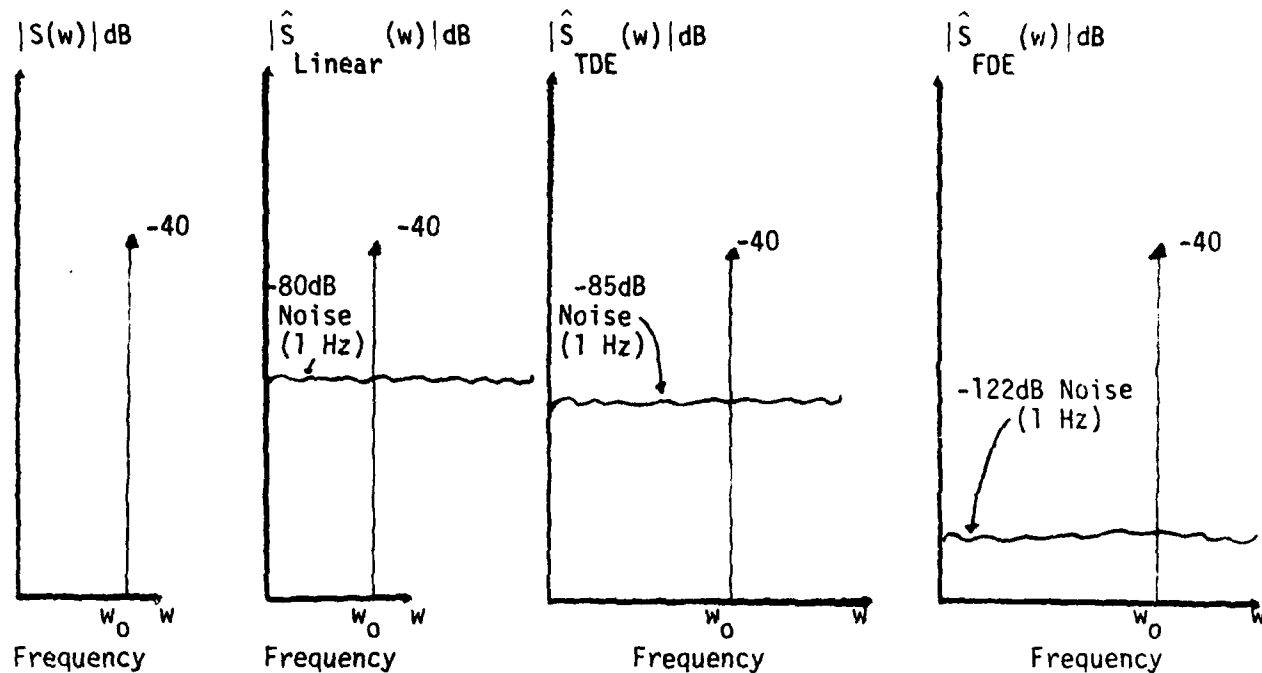


Figure 10e. Systems Performance with High Frequency -40dB Magnitude Input Signal

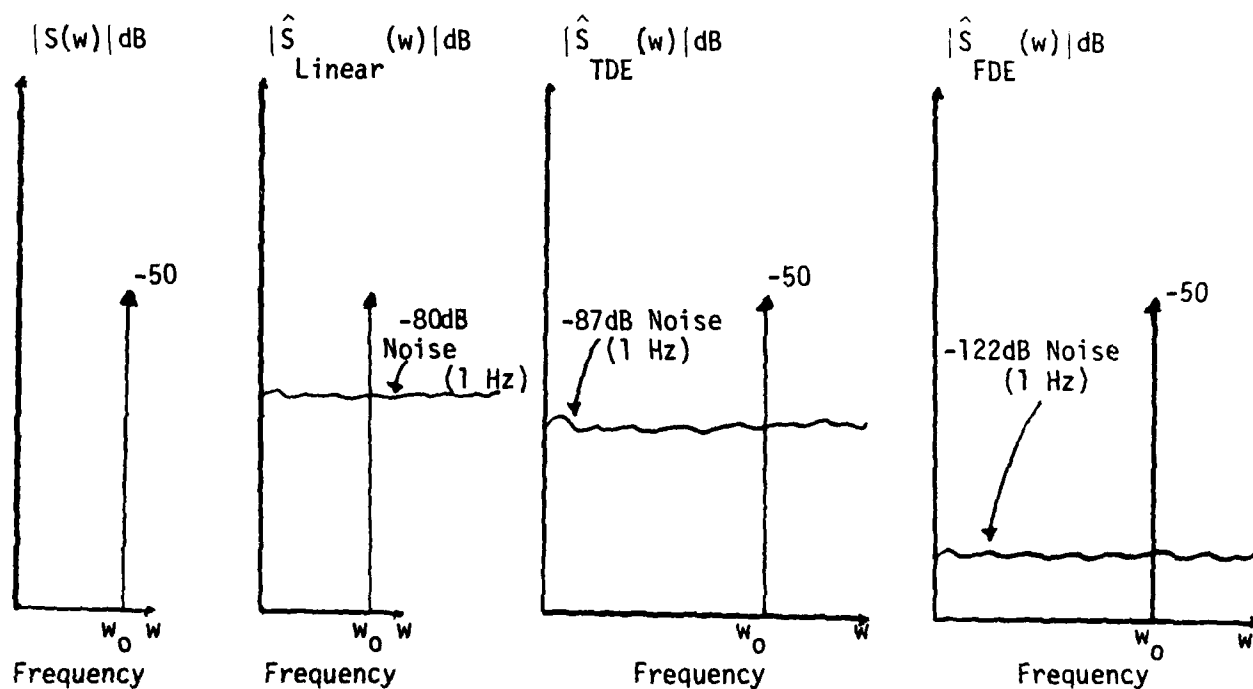


Figure 10f. Systems Performance with High Frequency -50dB Magnitude Input Signal

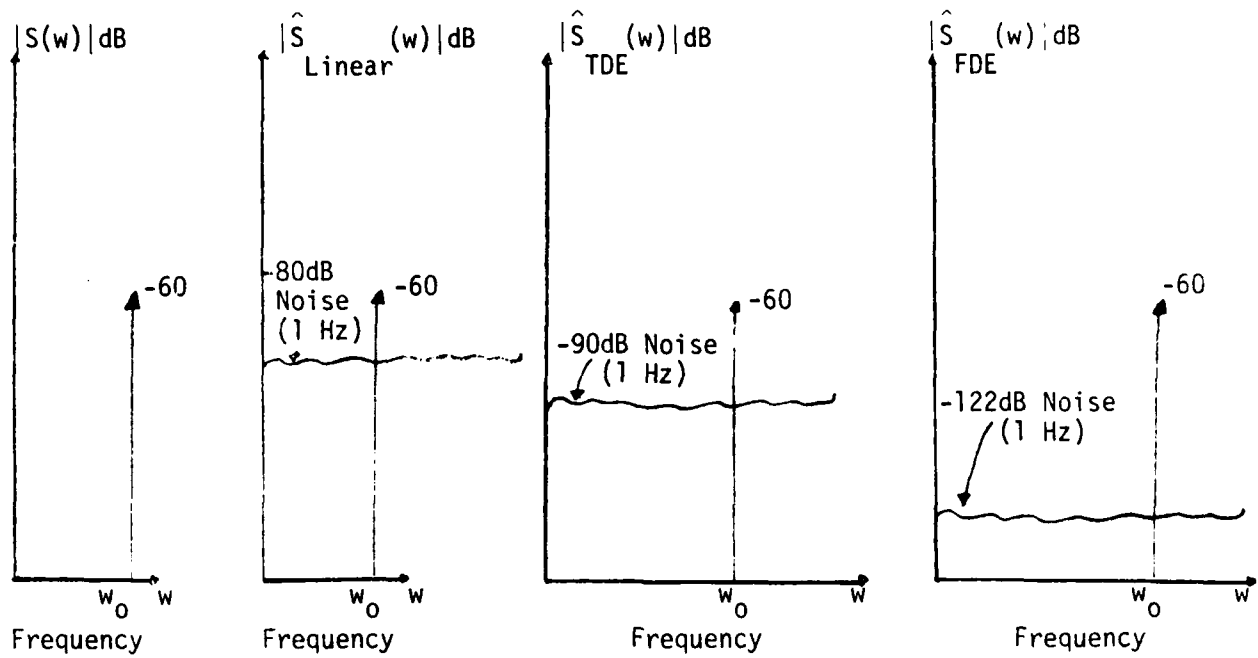


Figure 10g. Systems Performance with High Frequency -60dB Magnitude Input Signal

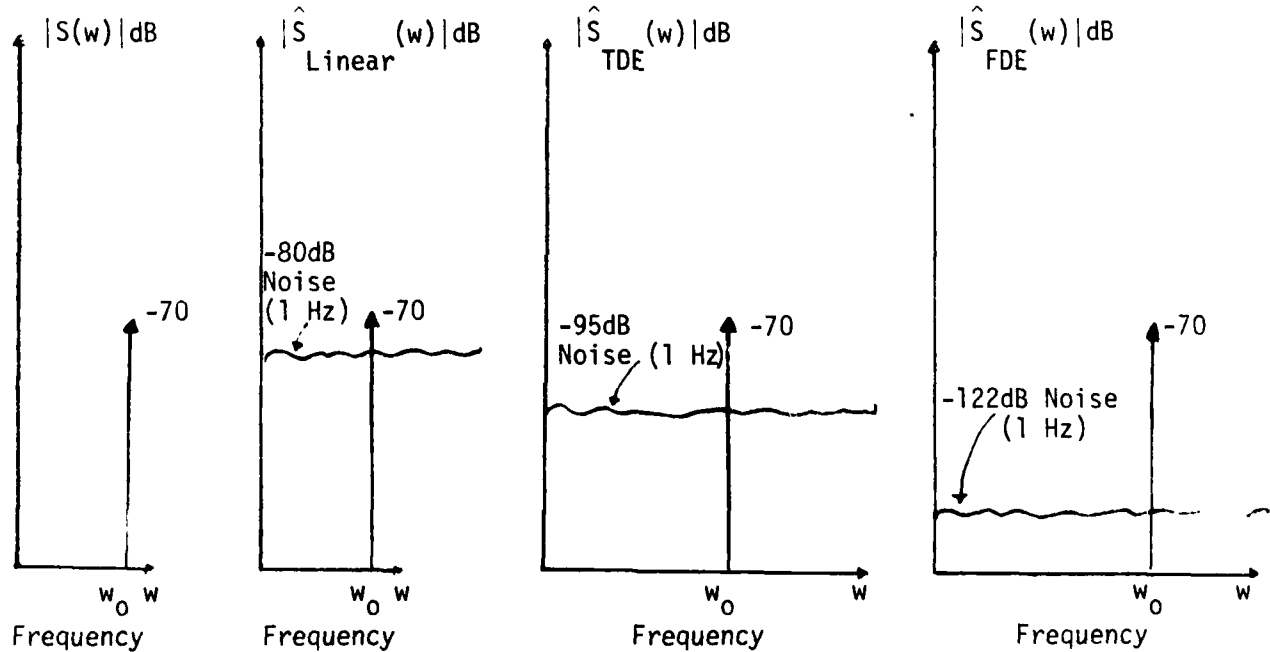


Figure 10h. Systems Performance with High Frequency -70dB Magnitude Input Signal

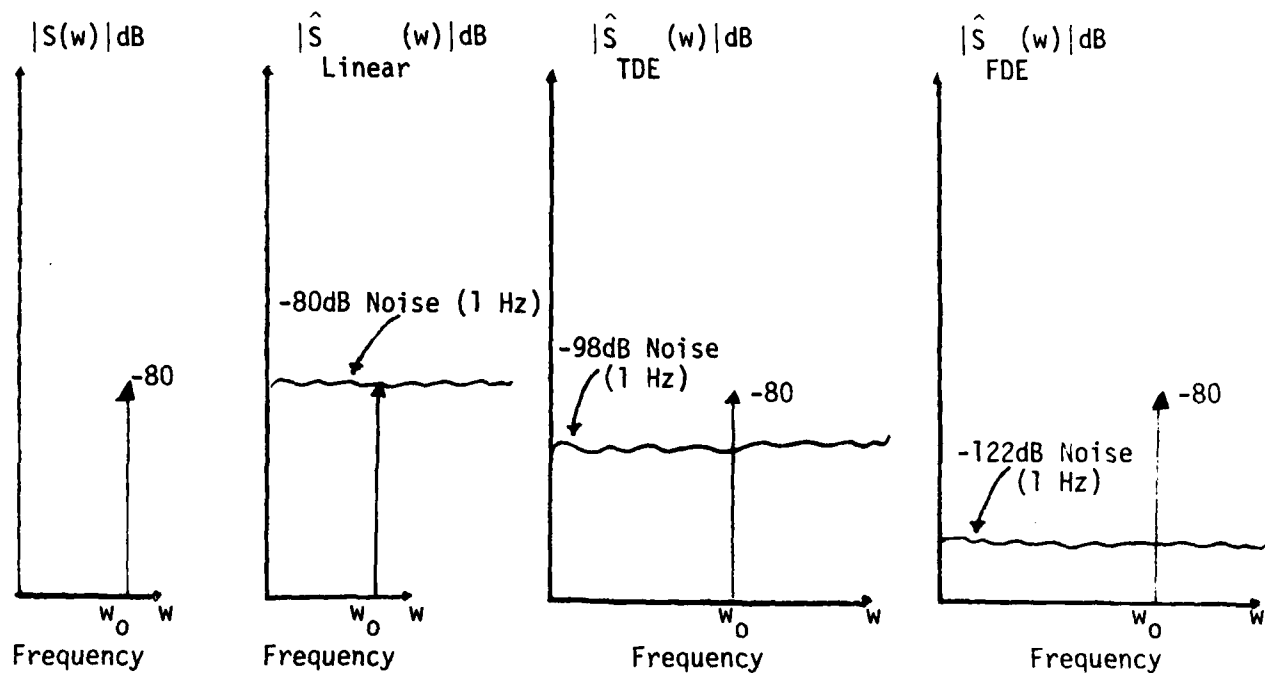


Figure 10i. Systems Performance with High Frequency -80dB Magnitude Input Signal

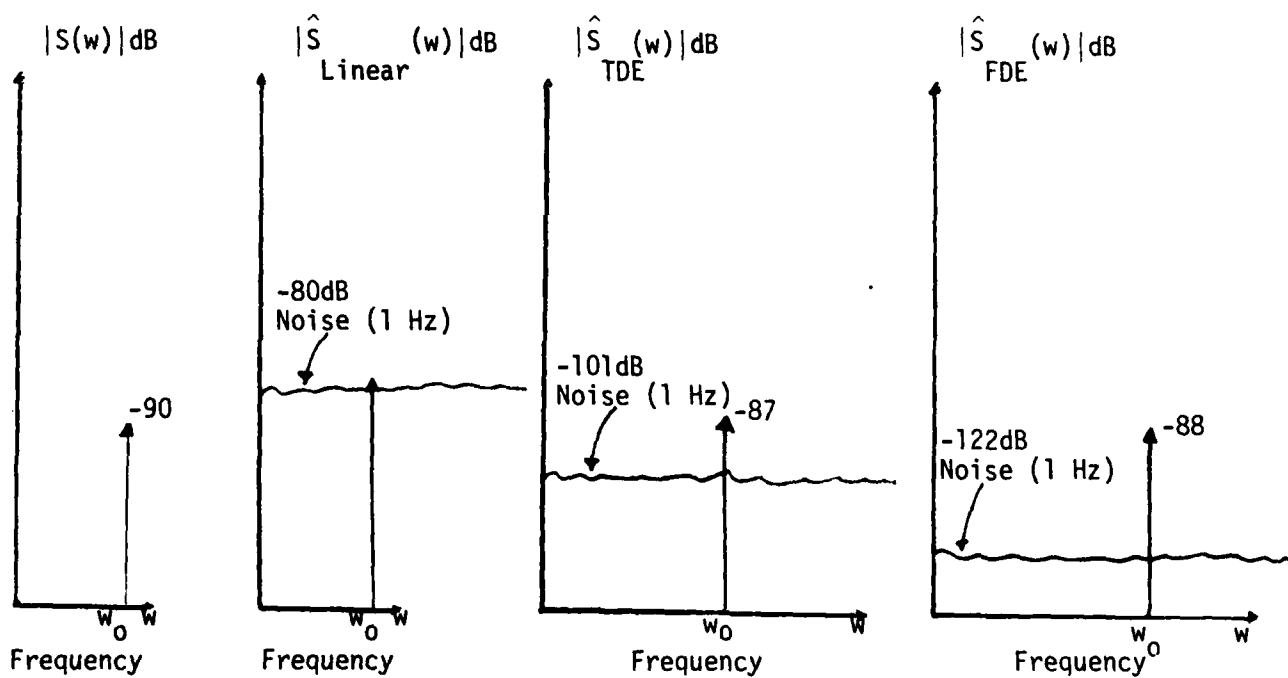


Figure 10j. Systems Performance with High Frequency -90dB Magnitude Input Signal

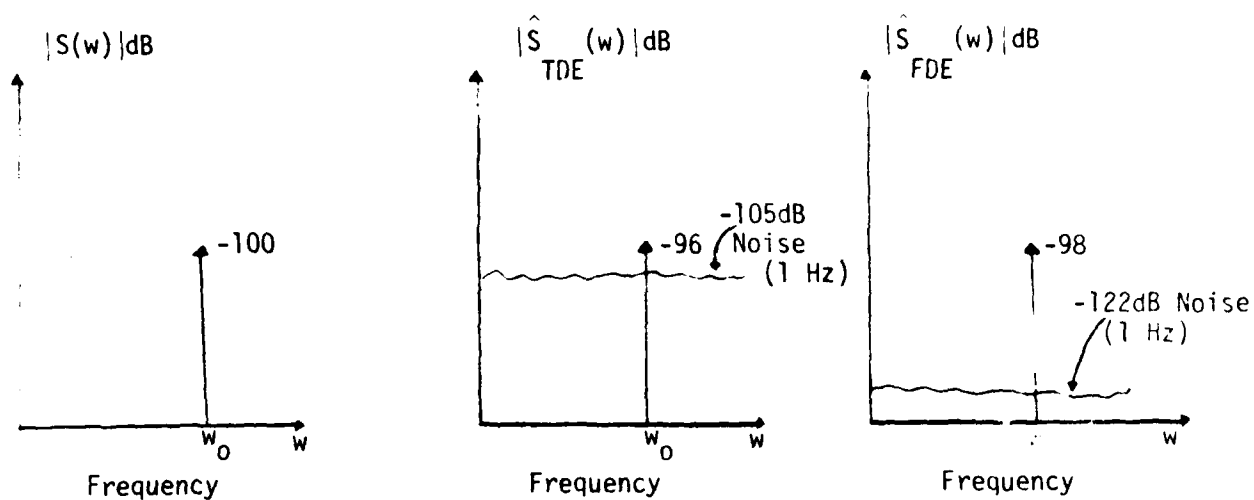


Figure 11a. Performances for -100dB Sinusoidal Input

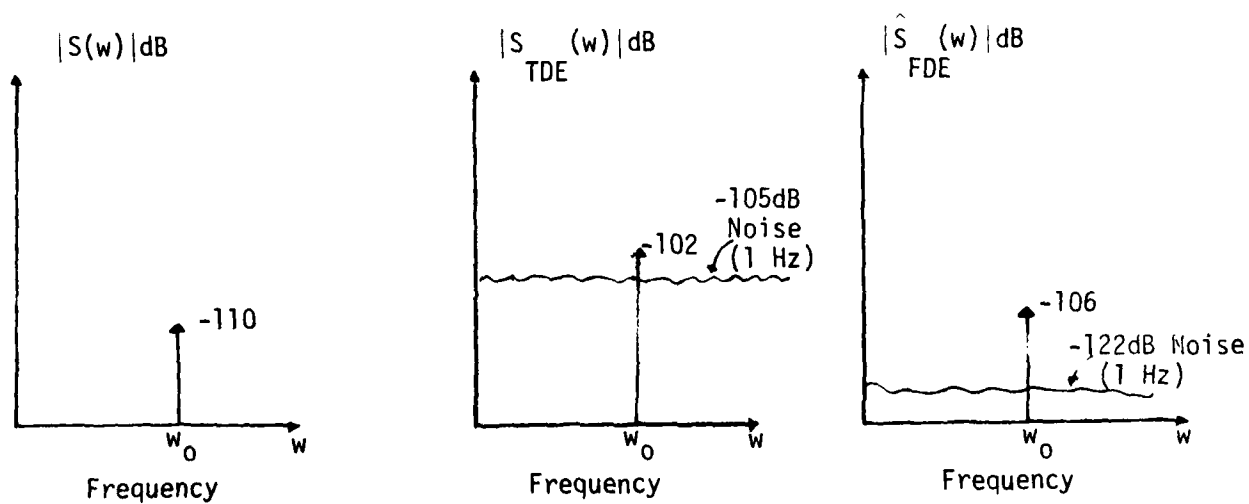


Figure 11b. Performances for -110dB Sinusoidal Input

VII. REFERENCES

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range from 80dB to approximately 120dB.

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